



PHD

## Interactive Feedforward in High Intensity VR Exergaming

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# Interactive Feedforward in High Intensity VR Exergaming

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A thesis submitted for the degree of Doctor of Philosophy

University of Bath

Department of Computer Science

April 2020

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## **Abstract**

VR exergaming is a promising motivational tool to incentivise exercise. It has been widely applied to low to moderate intensity exercise protocols; however, its effectiveness in implementing high intensity protocols that require lesser time commitment remains unknown. This thesis presents a novel method called interactive feedforward, which is an interactive adaptation of the psychophysical feedforward training method where rapid improvements in performance are achieved by creating self-models showing previously unachieved performance levels. Interactive feedforward was evaluated in a cycling-based VR exergame where, in contrast to how feedforward has typically been used, individuals were not merely passive recipients of a self-model but interacted with it in real-time in a VR experience. Interactive feedforward led to improved performance while maintaining intrinsic motivation. This thesis further explores interactive feedforward in a social context. Players competed with enhanced models of themselves, their friend, and a stranger moving at the same enhanced pace as their friend. Results show that competing with an enhanced model of a friend improves the performance and player experience the most. The main limitation of social interactive feedforward is that it is only suitable for players who have similar fitness levels as their friends to avoid underwhelming or overwhelming exergaming experiences. This limitation can be addressed by adapting the exergame intensity according to the player experience reflected by their affective state. Player experience estimation of VR exergame players by recognising their affective state could enable us to personalise and optimise their experience. Affect recognition based on psychophysiological measurements for high intensity VR exergames pose challenges as the effects of exercise and VR headsets interfere with those measurements. This thesis presents affective predictors based on gaze fixations, eye blinks, pupil diameter, and skin conductivity for affect recognition in high intensity VR exergaming. The findings of this thesis provide guidelines for interactive feedforward and affect recognition in high intensity VR exergames. In light of the findings, the research challenges that need to be overcome to implement affectively adaptive interactive feedforward in high intensity VR exergaming have been discussed.

# Preface

My research on VR exergaming is very close to my heart. I am a huge VR enthusiast and I love the alluring experience of being virtually transferred into an enthralling fantasy world with unlimited possibilities. I am very passionate about art, music, and emotionally charged cinematic experiences. My foray into gamification allowed me to indulge in my passion by developing appealing aesthetics and enticing gameplay to create memorable player experiences.

My experience as an athlete in my school days gave me a deep insight to the frenzy world of physical fitness. Competitive athletics demanded rigorous physical training and dedication. I remember the unique combination of being riddled with anxiety while feeling the thrill of an adrenaline rush before a race. Racing against fellow athletes was both physically and mentally trying. It required me to channel all my energy, focus, and motivation to overcome challenges such as muscular pain, fatigue, and self-doubt. The feeling of winning the athletic championships was euphoric and made it all worth it. I personally found that my athletic experience was both empowering and character-building. It has strengthened my determination, perseverance, and will-power to overcome various obstacles in life and chase my dreams.

My first-hand experience in physical fitness training gave me a good understanding of the hurdles faced by people when they try to commit to exercising regularly while juggling other personal commitments and a hectic schedule. I also know how rewarding physical fitness training can be and so I attempted to emulate my personal experience in my research. My PhD has been a wonderful learning opportunity. It was an emotional roller coaster ride filled with hard work and joy of discovery.

It enabled me to study different motivational techniques and I was struck by how effective feedforward was in improving performance without adversely impacting enjoyment. I have always been intrigued by the power of emotions and the huge impact it has on us. I am fascinated about the possibility of developing a dynamically adapting exercise game that allows the player to constantly experience positive emotions to facilitate exercise adherence. I thoroughly enjoyed every minute of my research experience and I will continue my exciting research in the amazing field of virtual reality exergaming.

I consider myself privileged to have worked with world leading experts in the fields of HCI and psychology; Dr. Christof Lutteroth, Prof. Eamonn O'Neill, and Dr. Michael Proulx. I express my heartfelt gratitude to my supervisor, Christof for his patient guidance. I thank him for proof-reading countless pages of my research despite his busy schedule and for his boundless enthusiasm for my project. I have learned a lot from his extensive knowledge of HCI and research in general. His penchant for perfection in research and helpful mentoring has helped me publish research papers in reputable international conferences. I sincerely thank my co-supervisors, Eamonn and Michael for their constant support and kind advice. They widened my horizon of research by suggesting interesting inter-disciplinary approaches. All of you have had a profound impact on me and helped me grow as a researcher.

I thank my husband and my inspiration, Dan for his unconditional love, emotional support, and for proof-reading my work. I hope to make him proud by not missing any of his revered Oxford commas. I thank my dear parents, Babu and Chithra, for their unwavering faith in me. I thank my little brother, Prakash, who is wiser beyond his years, for his sage advice, tough love, and for always having my back. I thank my dear grandparents, my uncle, and cousins, Raghav and Taru for always believing in me. I thank my lovely in-laws for their encouragement and support.

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# Publications

**The work in Part I led to the following publication:**

1. Barathi, Soumya C., Daniel J. Finnegan, Matthew Farrow, Alexander Whaley, Pippa Heath, Jude Buckley, Peter W. Dowrick, Burkhard C. Wünsche, James L. J. Bilzon, Eamonn O'Neill, Christof Lutteroth *"Interactive Feedforward for Improving Performance and Maintaining Intrinsic Motivation in VR Exergaming."* In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*, p. 408. ACM, 2018.

I did the literature review, contributed to the experiment design, ran the user study, did the quantitative and qualitative analysis, and wrote the first draft of the paper. My co-authors provided supervision, help and advice, contributed portions of the text, proof-edited the paper, and provided feedback for revisions.

**The work in Part III led to the following publications:**

2. Barathi, Soumya C., Michael Proulx, Eamonn O'Neill, and Christof Lutteroth. *"Affect Recognition using Psychophysiological Correlates in High Intensity VR Exergaming."* In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*, pp. 1-15. Association for Computing Machinery, 2020.

I did the literature review, proposed and implemented the experiment design, programmed the exergame design for the various experiment conditions, ran the user studies, did the quantitative and qualitative analysis, and wrote the first draft of the paper. My co-authors provided supervision, help and advice, contributed portions of the text, proof-edited the paper, and provided feedback for revisions.

3. Barathi, Soumya C., Michael Proulx, Eamonn O'Neill, and Christof Lutteroth. *"Guidelines for Affect Elicitation and Tracking in High Intensity VR Exergaming"* Momentary Emotion Elicitation and Capture Workshop at CHI 2020 Conference.

I did the literature review, proposed and implemented the experiment design, programmed the exergame design for the various experiment conditions, ran the user studies, did the quantitative and qualitative analysis, and wrote the first draft of the paper. My co-authors provided supervision, help and advice, contributed portions of the text, proof-edited the paper, and provided feedback for revisions.

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# Chapter 1

## Introduction

*“The journey of a thousand  
miles, begins with a single step”*

---

*Lao Tzu*

Virtual Reality (VR) has gone through a meteoric rise in popularity in the past decade. Although the idea of virtual reality is over half a century old, recent development in technology has just managed to make VR commercially viable. Gamification of exercising has been extensively studied by researchers and it has potential in making exercising more enjoyable [16]. Recent research shows VR exergaming as a promising exercise intervention to promote exercise adherence as it improves player experience [47, 300]. My thesis explores various aspects of VR exergaming and discusses the guidelines based on observations from my empirical studies.

### 1.1 Research Goals and Methods

My primary research goals are to improve exercise performance and player experience in high intensity VR exergames. I have done a thorough literature review of previous research over the years. I present a novel psychophysical training technique called interactive feedforward using self-modelling. A detailed empirical study investigating its efficacy and robustness shows that interactive feedforward



improves performance and maintains intrinsic motivation. This led me to exploring the application of interactive feedforward in a social context. Although social interactive feedforward was superior to self-modelled interactive feedforward, it was only applicable for co-players who were of the same fitness levels. I observed that social interactive feedforward may accommodate everyone if it is possible to adapt the exergame intensity according to the player experience as shown by their affective state. In order to achieve that, I designed experiments to identify the affective state of a player while playing a high intensity VR exergaming using psychophysiological correlates. I successfully identified affective predictors and discussed the research challenges that need to be overcome to implement affectively adaptive interactive feedforward.

### **1.1.1 Research Questions**

I investigated the following research questions in the first part of the thesis:

**RQ1** How effective is interactive feedforward in improving performance as measured by average power output while maintaining intrinsic motivation?

**RQ2** How robust are the effects of interactive feedforward to a player's awareness that the method is being used?

**RQ3** How do interactive feedforward and non-self-competition differ in terms of performance and intrinsic motivation?

**RQ4** How does enhancing the self-model by increasing the bike resistance differ from programmatically increasing the speed of the self-model in terms of performance improvement and intrinsic motivation?

I investigated the following research questions in the second part of the thesis:

**RQ1** How effective is social interactive feedforward in improving performance as measured by average power output when compared to conventional interactive feedforward?

**RQ2** How effective is social interactive feedforward in improving intrinsic motivation when compared to conventional interactive feedforward?

I investigated the following research questions in the third part of the thesis:

- RQ1** How do affective responses differ between sedentary gaming, exergaming, conventional exercise, and rest?
- RQ2** Which psychophysiological sensors are most suited for determining affect in high intensity VR exergaming?
- RQ3** What are the psychophysiological correlates of positive and negative affect in high intensity VR exergaming?

## 1.2 Thesis Overview

This thesis is divided into 3 main parts. To begin, Part I gives a background review on exercise adherence, introducing main concepts of gamification, self-modelling, and feedforward. I present the quantitative and qualitative analysis of interactive feedforward and discuss the results. I then move on to Part II and discuss social psychology with respect to social exergames. I present social interactive feedforward and compare it with self-modelled interactive feedforward. In Part III of the thesis, I discuss affect recognition and elicitation techniques. I present affective predictors to recognise underwhelming, overwhelming and optimal exergaming scenarios and discuss the research challenges of implementing affectively adaptive high intensity VR exergaming. All the experiments reported in this thesis received ethical approval from the Research Ethics Approval Committee for Health of the University of Bath (Reference: EP 16/17 191).

### 1.2.1 Chapter Breakdown

The chapter break-down is as follows:

- Chapter 2** The second chapter discusses the rise in sedentary lifestyle and its health risks. It lists the barriers to exercise adherence and how high intensity VR exergaming can potentially increase exercise adherence.
- Chapter 3** The third chapter gives an overview of related work on video games, gamification, and VR exergaming. It elaborates the motivations to play video games and also discusses the impact of real world exergames.

- Chapter 4** The fourth chapter introduces self-regulation and efficacy, video self-modelling, and feedforward.
- Chapter 5** The fifth chapter proposes interactive feedforward and presents the empirical study investigating its effectiveness in improving exercise performance and maintaining motivation.
- Chapter 6** The sixth chapter introduces social psychology theories such as self-determination theory, social cognitive theory, and discusses the importance of positive social interactions. It puts forth the notion of friend-modelled/social interactive feedforward.
- Chapter 7** The seventh chapter presents social interactive feedforward and compares its effectiveness in improving performance and motivation with self-modelled interactive feedforward. The chapter also recognises the need for affective adaptation of exergame intensity to make social interactive feedforward more widely applicable as opposed to being suitable only for friends who are almost of the same fitness level.
- Chapter 8** The eighth chapter discusses the related work regarding the need for optimal player experience to improve exercise adherence, user experience, immersion, and flow. Player experience is reflected by the current affective state of the player and therefore, it is important to recognise the player's affective state.
- Chapter 9** The ninth chapter reports related work on the advances in affective gaming and exergaming.
- Chapter 10** The tenth chapter presents empirical studies to recognise affect in high intensity VR exergaming.
- Chapter 11** The eleventh chapter discusses the research challenges of implementing affectively adaptive high intensity interactive feedforward and concludes the thesis.

## Part I

### Interactive Feedforward

# Chapter 2

## Exercise Adherence

*“Exercise should be regarded as  
tribute to the heart.”*

---

*Gene Tunney*

Exercising is described as a miracle cure and it can lower the risk of life threatening chronic illnesses such as cardiovascular problems, stroke, type 2 diabetes and cancer by up to 50% [1]. Our lifestyle has become primarily sedentary [351]. In this chapter, I have outlined the various health risks of leading a sedentary lifestyle and analysed the practical and psychological barriers to exercise adherence.

### 2.1 Health Risks of Leading a Sedentary Lifestyle

The evolutionary background of modern humans stems from 7 million years of active hunting and gathering [93]. According to an interesting article by Eaton et al., the genetic constitution of homo-sapiens has changed very little in the last 10,000 years and therefore, from a genetic standpoint we still have the gene pool of pre-agricultural hunter gathers. However, our lifestyle has drastically changed into being predominantly sedentary. This sudden change in lifestyle far exceeds any minor change in genetic composition resulting in a wide range of commonly occurring chronic degenerative diseases such as diabetes, hypertension and some types of cancers which was not the case in our pre-agricultural ancestors [103].

An article by Hambrecht et al. elaborates the health risks of our increasingly sedentary lifestyle and attributes several diseases such as cardiovascular diseases, hyperglycaemia, hypercholesterolaemia to name a few to lack of exercising [153].

Physical inactivity imposes a grave danger resulting in a global mortality of 3.2 million deaths and has been identified as the fourth leading cause of death globally. It results in 69 million disability adjusted life years [31]. It is also responsible for a substantial economic burden costing \$53.8 billion globally in healthcare expenditure and lost productivity in the year 2013 alone [94]. The American College of Sports Medicine (ACSM) recommends adults should do at least 150 minutes of moderate exercise or 75 minutes of vigorous exercise per week [262]. According to WHO, a staggering 81% of adolescents and 23% of adults are physically inactive which leads to an increased risk of several life threatening health hazards such as type 2 diabetes and cardiovascular disease [351].

## 2.2 Barriers to Exercise Adherence

Despite various awareness programs to communicate the physiological and psychological benefits of exercise, 40-65% of people enrolling for exercise programs typically drop out within 3-6 months [10, 11, 96]. Internal barriers such as lack of willpower, lack of time are more frequently cited as reasons for not exercising than external barriers such as lack of transport, cost [365]. Lack of time and motivation are the major barriers for most people [118]. The problem of lack of time can be mitigated by following high intensity exercise protocols which are twice as time efficient as moderate intensity exercise protocols while being equally effective [130, 262]. In order to effectively tackle the problem of lack of motivation, one has to understand what kind of motivation leads to long term exercise adherence.

Self-determination theory states that people are motivated to do a task if it meets the need to be autonomous, competent, and socially related to others [90, 290]. According to self-determination theory, there are three kinds of motivation: intrinsic motivation, extrinsic motivation, and amotivation, ranging from high to low based on the level of autonomy associated with them [105]. Intrinsic motivation refers to performing an activity because it is enjoyable by itself without the need

for other external rewards. Activities that let people experience competence and self-determination will repeat the activity out of intrinsic motivation [340]. Extrinsic motivation refers to doing an activity for an external reward or driven by external outcomes, e.g. losing weight and improving fitness. Amotivation refers to a state completely devoid of desire to indulge in a certain activity and resulting in a non-self-determined form of motivation [221]. It is neither intrinsic nor extrinsic motivation. Amotivated people feel incompetent and perceive that they are not in control of their actions [340]. It results in them eventually discontinuing the activity. Extrinsic motivation such as competitive pressure may lead to tension and feelings of compulsion, and can diminish intrinsic motivation [89,276]. Gamification can reduce the detrimental effects of competitive group dynamics [214]. Extrinsic rewards impede intrinsic motivation which in turn negatively affects gamification [152]. Therefore, I aim to develop an exergaming approach that intrinsically motivates the player.

Studies show that intrinsic motivation plays a crucial role in adherence to exercise [196,291,354]. Frederick et al. presented the Motivation for Physical Activity Measure consisting of three main motivation factors: interest/enjoyment, competence, and body-related motives. The results showed that interest/enjoyment and competence motivation which are instances of intrinsic motivation were related to positive psychological outcomes. In contrast, body-related motivation which has an extrinsic focus was associated with greater depression and anxiety [124]. Other studies also show that extrinsic reasons for exercising were found to cause stress and were significantly related to poorer psychological well-being and intrinsic motivations were significantly related to better psychological well-being [218,220].

Therefore, spontaneous enjoyment of physical activity i.e. intrinsic enjoyment leads to increased exercise adherence [345]. Teixeira et al. state that extrinsic motives are strongly correlated with short term exercise adherence whereas intrinsic motivation is strongly predicted with long term exercise adherence [321]. Even though extrinsic motives do not directly lead to exercise adherence, it is possible that one initiates exercising due to an external reward but starts intrinsically enjoying it leading to exercise adherence through the process called internalisation [106,290]. Regardless of whether initial motives to exercise are intrinsic or extrinsic, intrinsic motivation is one of the strongest predictors of long-term exercise adherence. The main

self-report measure of intrinsic motivation is considered to be interest/enjoyment. This implies that exercising has to be made enjoyable for it to become habitual. Enjoyable gamification of exercising using VR exergames that use time efficient high intensity exercise protocol could improve adherence as it mitigates the problem of lack of time and motivation.

## 2.3 High Intensity Exercise Protocol

High-Intensity Interval Training (HIIT) has emerged as a more time-efficient, yet equally beneficial, alternative to traditional moderate-intensity exercise [130]. It is considered to be one of the most effective exercise protocols for improvement [132, 206, 259]. Its reduced duration compared to continuous exertion exercise helps to address the major exercise barrier of lack of time. There is evidence that participants prefer HIIT over continuous exertion exercise protocols, enjoy it more and are therefore, more willing to exercise [33, 188, 330].

Despite these claimed advantages of HIIT, it remains a challenge to motivate people to exercise at a high intensity [120, 264] and adhere to a high-intensity exercise regimen [51, 261]. Therefore, my focus is on gamifying HIIT to enhance intrinsic motivation, and in particular, increase exercise intensity. One of the most well established and evaluated implementations of HIIT is the Wingate protocol, which consists of 30 second sprints at near maximum capacity, usually separated by  $\sim 4$  minutes of recovery, for a total of 2-3 minutes of intense exercise per session [176]. HIIT protocols of this kind can be “extremely demanding and may not be safe, tolerable or appealing for some individuals”, therefore, effective low-volume HIIT variations have been suggested for wider application to different populations, including people at risk of chronic metabolic diseases [131, 231]. I propose using a VR exergame to enhance performance and maintain intrinsic motivation in HIIT exercise.

## 2.4 Summary

A sedentary lifestyle is detrimental to health. Although, the American College of Sports Medicine (ACSM) advises that it is essential to do at least 150 minutes of



moderate intensity exercise or 75 minutes of high intensity exercise, many people do not follow the exercise recommendations [262]. This is primarily due to lack of motivation and lack of time. High-intensity interval training is twice as time efficient as moderate intensity exercise protocol while being just as effective thus mitigating the problem of lack of time. However, high intensity exercise protocol is physically exerting and it is difficult to motivate people to exercise at a high intensity.

## Chapter 3

# Gaming, Gamification, and Exergaming

*“I think everyone can enjoy games.”*

---

*Gene Tunney*

The gaming industry has been hugely successful in producing video games that are so captivating that players play video games hours on end. According to a market research report by the “State of Online Gaming 2018” based on responses from 3,000 international video game players, players spend an average of nearly six hours each week playing video games [2]. Components of gaming can be applied to exercising to promote intrinsic motivation.

This chapter begins by discussing the framework of game design. It is important to understand player motivations to play video games and demographic preferences so that we may develop interventions that get people exercising and leading less sedentary lifestyles. Along with applications in education [48], marketing [64], health [184], games can be a powerful driver in behaviour change towards physical exercise.

Virtual reality can be very captivating as it immerses the player in a virtual world which could potentially distract the player from painful exercise sensations. The

results of various studies on gamification of exercise show that gamification is successful in converting exercising into an enjoyable experience. Exergames can be defined as games that involve physical exercise as a mode of control. The impact of real world exergames such as Pokemon Go [343] , Dance Dance Revolution [246], and Wii Fit [141] which shows that exergaming has been successful in motivating players to exercise. Cycling VR exergames are a favourable choice from a safety perspective as players remain seated while wearing the VR headset. I have listed the various challenges of designing a VR exergame and how to overcome them.

### 3.1 Video Games

The video gaming industry is rapidly growing and is expected to reach over \$300 billion by 2025 and consists of 2.5 billion users according to a report by Forbes [121]. Players between the range of 26-35 years old spend eight hours 12 minutes per week playing video games and it has increased by more than 25 percent from last year. This report shows how popular video games are and its incredible potential in harnessing it to be applied in other activities such as exercising. In order to gamify exercising, one has to understand the components of gaming and why it is appealing to many.

Hunicke et al. formalised the approach to game design by presenting the Mechanics-Dynamics-Aesthetics framework [172]. The mechanics component of the framework consists of the rules and actions involved in the game. The dynamics component of the framework describes the behaviour of the mechanics based on player input during the game and the aesthetics component describes the affective reactions invoked in a player as a result of playing the game. Video games provide a whole new level of interactivity as opposed to other forms of passive media like films. Players are not just pulled into the narrative of the video game, they also dynamically interact with the mechanics of game to determine its output and become emotionally invested in the aesthetics of the game. I will describe my exergame using the format of mechanics, dynamics, and aesthetics framework to ensure easy replicability.

Video games can be used in a number of applications such as health. Schneider et al. examined the results of playing a game called Healthy critters that aims to

increase healthy eating and improve health behaviours [296]. The results showed that video games are highly acceptable to the players and they found significant increases in positive attitudes towards healthy eating. This study implies that video games can be applied to improve exercise.

### **3.1.1 Motivations to Play Video Games and Demographic Preferences**

A study by Ferguson et al. on children’s motivations for playing games revealed multiple motivations may fuel children’s interest in video games. Results showed that video game is played as a social activity. It was motivated by a desire for social interaction with others, fun way of spending time to avoid boredom and current stress level [113]. According to the shifts in demographic preferences analysed by Dalel et al., although video game players in the past were mostly male and below the age of 25, the number of female players and older players have been constantly increasing [86]. This shift is very encouraging, and it implies that games are widely appealing to a wider section of demographics.

### **3.1.2 Effects of Playing Video Games**

Studies show a number of psychological and cognitive benefits when playing video games regularly. According to an extensive literature review spanning developmental, positive, media, and social psychology research by Granic et al. playing video games may foster real world psychosocial benefits [140]. A study Whitbourne et al. analysed feedback of 10,308 adults between the age range of 18 to 80 years on a social online game, Bejeweled Blitz (BJB). All players specified the social element of playing with their friends as the primary motive to play. Middle-aged players’ main motive to play was as a stress relief and older players mentioned that they enjoy the game’s challenges. Younger players attributed feeling sharper and improved memory to the game. Older players felt the game enhanced their visuospatial skills [350].

A study by Boot et al. showed that expert gamers were better than non-gamers in basic cognitive skills. Experts performed better at tracking fast moving objects, better retrieval from visual short-term memory and better task switching [49]. A

meta-analysis of 217 studies on examining the magnitude, moderators, durability, and generalisability of training on spatial skills shows that video game players performed substantially better. Video game players had better working memory and smaller attentional blink [339].

A study by Adachi et al. showed that playing strategic video games predicted higher self-reported problem-solving skills than playing less strategic video games [3]. They also showed an indirect association between strategic video game play and academic grades. Their findings showed higher self-reported problem solving skills which was a predictor of playing strategic video games predicted higher academic skills. According to a study by Griffiths et al. videogames are appealing across the demographic boundaries, can help with goal setting and behavioural change [142]. They also help us examine traits such as self-esteem, self-concept, while being fun, providing elements of interactivity, and allowing players to experience novelty, curiosity, and challenge [142]. Hall et al. provide a review of related work on health outcomes of playing video games. Their review showed significant positive effects mental, physical, and social health outcomes as a result of playing games [149]. These multiple benefits give all the more reason to use games for exercising.

However, a study by Carnagey et al. showed that players who played violent video games showed less physiological arousal when exposed to real-life violence than non violent gameplayers which could imply physiological desensitisation to violence [62]. Another study by Bartholow et al. shows that video game violence exposure is positively correlated with self-reported aggressive behaviour [32]. Furthermore, individuals with low exposure to video game violence exhibited more aggressive behaviour after playing a violent video game than a non-violent one. Players with high exposure to violent video games demonstrated high aggression levels irrespective of the video game. These negative effects of violent video games need to be considered when designing games.

## 3.2 Gamification

Gamification is defined as “a process of enhancing a service with affordances for gameful experiences in order to support user’s overall value creation” [173].

It refers to the process of using the components of games and its features to enhance motivation in numerous potential applications in education [48], marketing [64], health [184] to name a few. Hamari et al. investigate the relationship between utilitarian, hedonic, and social motivations and continued intention to use gamification [151]. Utilitarian services refer to services that are designed to be practical and their use is extrinsically motivated. In contrast to that, hedonic services refer to services that are designed to be intrinsically motivating. Their results indicate that the association between utilitarian benefits and use is mediated by the attitude towards gamification while hedonic aspects have a direct positive relationship with use. They conclude that that hedonic, intrinsic motivators drive the use of gamification. Utilitarian and social extrinsic motivators affect the attitude. This in turn impacts the intentions for using gamification.

A study by Bonde et al. shows that biotechnology education can be improved by using gamified laboratory simulations [48]. Their results showed significant increase in both learning outcomes and motivation levels when compared with conventional teaching. A study by Cechanowicz et al. on effects of gamification on participation and data quality in a real-world market research domain shows that gamifying market research surveys significantly improves participation [64]. It was also found to enhance motivation of the players. They found no significant effect of respondent age, gender, panel tenure, and gaming experience, which implies that gamification can improve motivation across all of these demographic factors - although the type of game affects the demographics that are appealed by it [272]. Gamification has also been extensively applied in exercising as discussed in section 3.4.

According to Hamari et al., gamification of strictly rational behaviour such as gamification of e-commerce sites might be difficult [150]. According to the suggestions on practical implications for design of gamification based on demographic differences, Koivisto et al. suggest that using social features in the service is beneficial for creating sustainable and engaging gamification [198]. Furthermore, applications that invoke mental and physical activity, enhance social connectedness, and provide immediate feedback while improving self-efficacy could motivate the use of technology among older people [13, 85, 175, 198]. Therefore, social exergaming which meets the criteria listed by them can be used to motivate the

use of technology among older people.

Aparicio et al. analyse the psychological and social motivations of humans in relation to self-determination theory which posits that intrinsic motivation can be maintained by satisfying the need to be autonomous, competent, and socially related to others [90,290]. Therefore, in order to maintain intrinsic motivation in exergaming, it has to fulfil the needs of autonomy, competence, and relatedness. This could be done by allowing people to control the game through their actions giving them a sense of autonomy, presenting them with an optimal challenge to give them a sense of competence, and providing positive social interaction to give them a sense of relatedness.

Aparicio et al. propose to make the process of gamification effective. The first step is to identify the main objective i.e. the purpose of the task one wants to gamify. The second step is to identify a transversal objective i.e. one or more underlying objectives that capture the interest of a person. The third step is to select the game mechanics in such a way that it enhances the autonomy, competence and relatedness of the player. With respect to gamification, this can be done by using a configurable interface to increase autonomy, provide optimal challenge to increase competence, and provide a social element to increase relatedness. The fourth step is to analyse the effectiveness of the system [12]. I will follow these steps to gamify exercising.

### 3.3 Immersive Media, VR, and VR Applications

Immersive media describes technology that enables the user to perceive a digitally simulated reality [204]. It comprises of different types such as virtual reality, augmented reality and mixed reality. Virtual reality is a computer-generated simulation of a three-dimensional environment which enables real time user interaction. Augmented reality superimposes digital media on the user view of the real world thus augmenting reality. Mixed reality comprises of both real and virtual entities producing a hybrid environment. Milgram et al. view augmented reality and virtual reality as two concepts that lie at opposite ends of the Reality-Virtuality (RV) continuum as shown in Figure 3-1 [234]. The left end of the continuum represents an environment consisting of only real objects and the right

end represents a purely virtual environment. The mixed reality environment is one in which both real and virtual objects are presented in the same display and they could be placed anywhere in the RV continuum.

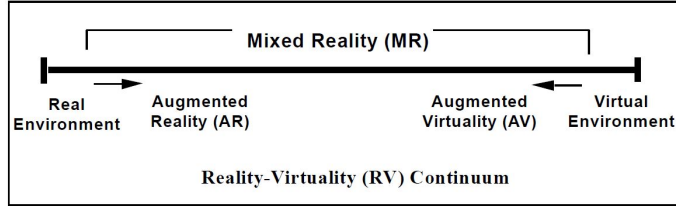


Figure 3-1: Representation of Milgram et al.'s RV continuum [234]

According to the article by Rose, immersive media goes beyond engagement and enables blurring the lines between the illusion and reality so much so that the audience forgets that it's an audience giving it enormous impact [284]. According to Jayaram et al., main components of VR are immersion in a 3D environment through stereoscopic viewing, user feels like a part of the virtual environment achieved through tracking, engaging the senses of the player, and realistic virtual environment [181]. Virtual reality has also been used in a number of applications in military [277], health care [125, 292, 305], fashion [266], education [229] as discussed below.

### 3.3.1 Military

Virtual reality is useful in military training when simulating hazardous combative situations and in the treatment of post-traumatic stress disorder. A study shows that patients reported a significant decrease in the self reported symptoms of post-traumatic stress disorder and 62% of patients showed a reliable change when exposed to virtual reality exposure therapy [277].

### 3.3.2 Mental Health

Freeman et al. did a review of 285 empirical studies on using virtual reality in the treatment of mental health disorders such as anxiety, schizophrenia, substance related disorders and eating disorders. Their review results showed that the most established finding was that virtual reality treatments can reduce anxiety



disorders. They identified that virtual reality is effective in simulating reality which enhances psychological therapies. They concluded that virtual reality along with user experience driven design has the potential to transform the assessment, understanding and treatment of mental health problems [125]. This shows that VR is powerful in simulating affective scenarios for exposure therapy purposes which can be applied in VR exergaming to create effective positive affective experiences.

### **3.3.3 Rehabilitation**

Shin et al. studied the effects of virtual reality-based rehabilitation on distal upper extremity function which is responsible for doing activities like holding objects in stroke survivors and health-related quality of life using a single-blinded, randomized controlled trial. Their results showed that virtual reality based rehabilitation merged with standard occupational therapy might be more effective than conventional rehabilitation for improving distal upper extremity function and health related quality of life [305]. This could possibly be extended into VR exergaming for stroke rehabilitation purposes.

Saposnik et al. studied the efficacy of using VR exergaming in stroke rehabilitation. They ran a pilot study consisting of a randomised, single blind clinical trial of 2 parallel groups of stroke patients. They compared the Nintendo Wii gaming system with the recreational therapy such as playing Jenga. The results showed that VRWii group revealed a significant improvement in motor function when compared to the recreational therapy group. They identified that VRWii is a potentially effective alternative to enable stroke rehabilitation [292]. It would be useful to apply other kinds of physiotherapies in VR exergaming.

### **3.3.4 Shopping**

Park et al. propose that virtual reality can be a cost-effective way to test store designs by letting customers imitate real shopping experience [266]. They examined shopper interaction by recruiting 40 females. Their results showed that the immersive experience of virtual reality was positively related with important shopping outcomes such as pleasure, attitude toward virtual stores, and purchase intention implying that it can be used to improve consumers' experience and

engagement. Similarly, VR can also possibly imitate a gym experience from the comfort of one's home and improve player experience while exercising.

### **3.3.5 Education**

Merchant et al. did an analysis of the influence of design principles in VR based games or simulations in higher education settings [229]. Their results indicate that games show higher learning gains than simulations and virtual worlds. According to a literature review about the use of VR in education, it enhances the student's involvement and motivation while increasing the range of learning styles enabled [126].

Considering the success of the various applications of virtual reality in different sectors, I chose virtual reality as a medium for gamifying exercise because it completely immerses the player in a virtual world with potential to provide an effective distraction from unpleasant exercising sensations like muscular pain and fatigue.

## **3.4 VR and Non-VR Exergaming**

### **3.4.1 Effect of Gamification of Exercise**

VR and non-VR exergames have been extensively studied over the years and many of them show potential in increasing exercise performance and player experience as discussed below. A study by Bailey et al. examined the relative effect of exergaming on energy expenditure among children. They compared treadmill walking and Dance Dance Revolution, LightSpace (Bug Invasion), Nintendo Wii (Boxing), Cybex Trazer (Goalie Wars), Sportwall, and Xavix (J-Mat) which are all exergames. Their results show that exergaming improved energy expenditure above rest and enjoyment of all the exergames was high but was found to be the highest for children in the highest BMI percentiles [16].

Biddiss et al. systematically reviewed the levels of metabolic expenditure in children [41]. Their results show that exergaming enables light to moderate intensity exercise. A study by Kari et al. shows that some positive effects of gamification of exercise are the ability to track exercises, follow personal

development and self-competition to name a few [193]. Some negative effects named by them are software errors and experiencing usage problems.

A search for related work on implementing high intensity exercise protocols in VR exergaming reveals that up until 2018 not much research had been done on it and it was a completely novel area of research. Some studies had successfully implemented high intensity non-VR exergames [235, 236]. However, implementing high intensity exercise protocols in a *virtual reality* exergame can possibly be more challenging due to impeding challenges such as wearing a VR headset while exercising at a high intensity and VR sickness. These challenges have been discussed in more detail in section 3.4.5.

A study by Shaw et al. examined the impact of competition and cooperation with virtual players on exercise performance in a VR exergame. The first experiment evaluated the influence of competing with a self-model, playing the exergame with a virtual trainer. The second experiment tested the impact of competition with a virtual trainer and cooperation with a virtual trainer. The results imply that the competing with a self-model was more enjoyable than playing with the virtual trainer. The results of second study implied that the competing with a virtual trainer resulted in better exercise performance and caloric expenditure, and was also found to be more motivating [300].

A study by Michael et al. introduce a novel method to elicit positive racing experience which is a rush of excitement, hope, stress, and anxiety combined with the competitive drive to win typically experienced by athletes in non-athletes [232]. They achieved this by using a high-intensity cycling VR exergame that saves the performance of the player. Players race against a group of self-models moving at the pace of their previous performances and one self-model projecting their future enhanced performance. They did a longitudinal study spanning a month and their results show an improvement in performance, intrinsic motivation and flow when compared to a non-competitive condition.

A study by Koulouris et al. examined the influence of using customised avatars and the process of customisation of a self-model in a high intensity VR exergame [200]. They tested the effects of customisation and how realistic and idealistic self-models can affect performance and player experience in a VR exergame. Their first study

analysed the effects of self-model type by recording the players baseline and comparing the results of competing with a generic self-model and a customised realistic self-model. Their results show that customisation of self-model can increase identification and this identification enhances intrinsic motivation and performance improvement. The results of their second study showed that idealised customisation of a player's self-model lowered exercise performance and their third study found that enhancing realistic self-model did not negatively impact effects.

Ioannou et al. tested virtual performance augmentation in an immersive jump and run exergame [177]. They achieved virtual performance augmentation by exaggerating the physical abilities in a VR exergame. Their results show that virtually augmenting running and jumping can increase intrinsic motivation, perceived competence and flow, and may also increase motivation for physical activity in general.

### **3.4.2 Impact of Real-world Exergames**

Hawthorne effects or observer effects refer to participants exhibiting a certain kind of behaviour exclusively because they are being observed [226]. Laboratory studies have been shown to increase Hawthorne effects and this poses generalisability problems [111, 226]. Real-world exergames provide an excellent opportunity to study the widespread impact of exergaming in improving exercise performance and player experience via longitudinal studies and large sample sizes. They are also likely to lower the influence of Hawthorne effects as these studies involve players playing the exergame out of their own accord in non-laboratory premises. Pokemon Go is an augmented reality mobile application which allows the players to interact with virtual creatures called Pokemon by virtually appearing in real-world locations using the Global Positioning System. Pokemon Go is a great example of an exergaming application successfully implemented commercially and by the year of 2019 the game had crossed billion downloads. Many user studies discuss the real-world impact of the exergame.

A study by Althoff et al. studied the influence of Pokemon Go on exercising. They identified Pokemon Go players via search engine queries and calculated physical activity using accelerometers. Their results implied that Pokemon Go

resulted in a significant increase in exercise over a span of 1 month and some active players showed greater than 25% raise in exercising. Pokemon Go has enhanced physical activity across a wide range of demographic categories such as age, gender which shows its potential in improving public health [7]. According to a study by Wagner et al., they found a large increase in exercising as a result of playing Pokemon Go [343]. Players were asked to report the number of days they engaged in 30 or more minutes of exercising with Pokemon Go before and after installing Pokemon Go. Wagner et al. found a significant increase in the percentage of players who engaged in the recommended amount of physical activity. According to their results 31% of the players satisfied the recommended activity levels before installing Pokemon Go and it increased to 75% after they started playing the game. According to a study by Nigg et al. [254], playing Pokemon Go increased physical activity by about 50 minutes per week and reduced sedentary behaviour by about 30 minutes per day. A study by Barkley et al. surveyed walking and sedentary behaviour among a sample of 358 college players who had installed Pokemon Go. Their results showed that playing Pokemon Go increased physical activity and decreased sedentary behaviour [30].

Dance Dance Revolution(DDR) is a popular dance based video game. A study by Hoysniemi et al. examined the response of 556 respondents to an online questionnaire regarding the frequency, motivation to play, social relationships, player experience and physical exercise factors [171]. Their results showed that playing DDR enhances social relationships and physical health of the player by increasing endurance, muscle strength and sense rhythm. A study by Murphy et al. showed that DDR can potentially be used as a viable alternate exercise to improve cognitive function among the elderly and to motivate sedentary people to exercise [246].

A study by Graves et al. examined the physiological cost and enjoyment of Wii Fit in adolescents, young adults, and older adults [141]. They analysed the cardio-respiratory and enjoyment measurements during sedentary gaming, Wii Fit exergaming and treadmill walking and jogging. Their results showed that heart rate during Wii exergaming was significantly higher than when they were playing a video game but was significantly lower than treadmill exercise. The enjoyment level was higher during Wii exergaming activities of balance and aerobics compared

with treadmill walking and jogging. They conclude that Wii Fit is suitable for light-to-moderate intensity physical activity.

These studies show that commercial exergames launched in the real-world have been very successful in increasing various factors such as physical activity and intrinsic motivation which lends further credibility to the choice of using exergames. One common observation among these studies is that commercial exergaming is effective in implementing moderate intensity exercise protocols but its effectiveness in gamification of high intensity exercise protocol that is twice as time efficient is unknown.

### **3.4.3 Cycling Exergames**

Some VR exercise games make use of an exercise bike, which allows players to remain seated and reduces the risk of injury or VR sickness [47, 302]. Shaw et al. found that an exergame increased enjoyment and motivation compared to conventional cycling exercise, and that the use of an HMD compared to a 2D screen led to further improvement in motivation [301]. Although exergames can be enjoyable, they are often not vigorous enough to replace traditional physical activity; “a biking exergame design requires a precise balance between interaction design and exercise physiology in order to be both engaging and beneficial to health” [146].

Game mechanics that encourage players to exercise at a higher level of intensity through rewards were found to be effective in increasing exertion levels and enjoyment [195]. Similarly, competition in exergaming, especially self-competition, was found to be effective in eliciting higher levels of exercise and enjoyment [300]. However, for players with low fitness or low self-efficacy, competition in exergames can highlight their inadequacies and cause “more damage than good” [214]. My focus is therefore, on competition-based gamification techniques that intrinsically motivate players to exercise at a higher intensity.

### **3.4.4 Player Experience in Exergames**

Immersion – the degree of involvement in a game [55] – plays an important role in motivation and enjoyment of exergaming [182]. Ijsselstein et al. showed that

in a highly immersive exergaming environment players reported more interest, enjoyment, perceived competence and control, as well as cycling faster [174]. A study by Banos et al. shows that, the immersive nature of VR increased enjoyment and enhanced attentional distraction in overweight children during exercise, motivating them to perform better [27]. Johnson et al. found that dissociation lowered the rate of perceived exertion [183]. This indicates that dissociation from exercise through immersive VR can allow players to exert themselves more, improving performance, enjoyment and motivation.

A concept related to immersion is flow [82, 110], which is an ideal psychological state of energised focus, enjoyment and complete absorption in an activity where the skills of an individual are balanced with an adequate challenge. According to typical models of flow such as the experience fluctuation model depicted in (Fig. 9-1) [222, 223], challenges that are too easy lead to boredom, and challenges that are too demanding lead to anxiety. Flow has been discussed in the context of exergames [306], where flow can be subdivided into a psychological component balancing the player’s perceived skill with perceived challenge (“attractiveness”) and a physiological component balancing a player’s fitness with the intensity of the exercise. Consideration of flow is useful when trying to improve performance while maintaining intrinsic motivation.

### **3.4.5 Challenges of designing a VR exergame**

A study by Shaw et al. outline the challenges of designing a VR exergame and how to mitigate them [302]. They identified the following challenges that come with designing exergames on a virtual reality platform.

#### **VR Sickness**

The first challenge they identified is that improper game design would lead to motion sickness when using a VR headset. Merhi et al. examined motion sickness in VR. Their results showed that motion sickness was more common when players are standing [230]. They explain that the motion sickness is greater when players are standing because of postural instability and the body is more stable in a seated posture than in a standing posture.

Motion sickness can also occur as a result of sensory mismatch caused by an incongruence between the sensory inputs from the visual system, vestibular system which is mainly responsible for a sense of balance and proprioceptors which gives a sense of position [275]. Shaw et al. reduced potential sensory mismatch by accurately tracking the player's head and mapping it into the exergame. They also emphasise the importance of a good frame rate and proper calibration to mitigate motion sickness. They found incidence of motion sickness when players cycled down ramps or fell down pits in the exergame and they believe that it was caused by a sensory mismatch. They propose that it can be mitigated by using straight lanes or by providing vestibular stimulation [215].

### **Appropriate View**

According to Shaw et al. the first person perspective is more conducive to immersion as the camera orientation is linked to the orientation of the player's head which makes the interaction with environment intuitive [302]. Kilteni et al. define self-location as "determinate volume in space where one feels to be located" and state that self-location is greatly influenced by the visuospatial perspective [197]. Furthermore, a study by Petkova et al. examines the impact of visual perspective in full-body ownership which is attributing self to an external body [270]. Their results show that first person perspective is crucial for instigating full-body ownership. Their results imply that full body ownership of an external body is a constructive process where visual, tactile, and proprioceptive (responsible for a sense of position and movement) signals are integrated in ego-centric coordinates [270]. Based on the related work on the importance of first person perspective on inducing self location [197] and full-body ownership [270] of the character in the VR exergame and enhancing immersiveness, I use first-person perspective in my VR exergame experiments.

### **Health and Safety Risks**

Shaw et al. identify the following health risks associated with VR exergaming [302]:

1. A warm up must be included in the exercise protocol to avoid injuries and the warm up should involve the same muscles as the exergame exercise.



2. The cables attached to the VR headset and other devices must be out of the player's way to avoid them tripping over it.
3. There is a possibility of balance problems as a result of postural instability and disequilibrium which can be mitigated by ensuring the player is seated on an upright exercise bike with hands on the handlebar.
4. The orientation of dodging motion of obstacles should be small or the game should allow avoiding obstacles by the tilting of player's heads to avoid the problem of players hitting the bike's display.

I ensured that I adhered to all the safety rules in my experiments.

### **Feedback Latency**

Feedback latency in this context refers to the delay in the game response to a player's input. Shaw et al. identified that feedback latency was disliked by the players and they were disturbed by it which implies that it could adversely affect player experience [302]. Therefore, I ensured that I reduced feedback latency to the minimum possible extent in my exergame by ensuring quick game feedback to player's input.

## **3.5 Summary**

The review of related work in this chapter shows that the hugely popular gaming industry churns out video games that intrinsically motivate players to play them. The core elements of video games can be transferred to various applications in other fields such as education, sports through the process of gamification in order to improve enjoyment. VR exergaming is an effective intervention for exercise adherence as it combines the enjoyable gamification element with the immersive virtual reality medium thus intrinsically motivating players to perform better. Therefore, I choose VR exergaming to implement the challenging high intensity exercise protocol to intrinsically motivate players to achieve the required exercise intensity.

# Chapter 4

## Self-Modelling and Feedforward

*“Better to be drawn by images of  
the future than driven by ghosts  
of the past.”*

---

*Peter W. Dowrick*

Self-regulation refers to directing one’s own behaviour to meet a certain self-imposed standard [46]. It plays an important role in behaviour change. Self-efficacy refers to an individual’s belief in achieving a certain goal [23]. Self-efficacy affects the goals set by an individual [23, 212] and self-regulation impacts how they direct their behaviour to achieve the said goal [366]. Therefore, both self-regulation and self-efficacy play an important role in setting exercise goals and regulating one’s behaviour in order to achieve the exercise goal. This chapter introduces feedforward (i.e. enhanced self-modelling) which is a psychophysical motivation technique to achieve performance improvement in a short span of time. Self-modelled feedforward results in increased self-efficacy, self-regulation, intrinsic motivation and performance [71]. Therefore, feedforward could potentially be used in positively modifying exercise behaviour leading to exercise adherence.

## 4.1 Self-efficacy and Self-regulation

Self-efficacy is defined as one's belief in their ability in successfully achieving a goal. Self-efficacy impacts goal setting. The higher people's self-efficacy, the higher they set their goals, and the more dedicated they are towards achieving it [23, 212]. I note that it is contradictory because self-efficacy cannot influence goal setting if it is a belief in goal achievement. Cognitive engagement refers to the amount of effort that one is willing to invest and how long they persist to learn the task at hand [285]. Walker et al. examined the motivational characteristics of students including intrinsic/extrinsic motivation and self-efficacy as predictors of cognitive engagement. Their results show a positive correlation of self-efficacy, intrinsic motivation, and identification with cognitive engagement whereas extrinsic motivation only predicted shallow cognitive engagement [344]. Their results are unclear if identification is a prerequisite to cognitive engagement or if it is an outcome of being intrinsically motivated and having high self-efficacy.

Self-regulation is defined as a series of steps to reach a personal goal by controlling one's behaviour over time and across contexts to achieve self-chosen goals [46]. It is important to achieve self-regulation because it plays a vital role in behaviour acquisition. This implies by extension that better self-regulation could lead to enhanced exercise adherence. The process of self-regulation involves intrinsic thoughts, feelings, and actions that are influenced and cyclically customised in order to achieve personal goals [366]. Self-regulation is considered an ongoing attempt of adaptation depending on the assessment of the previous performance amidst continually changing personal, behavioural, and environmental factors. High self-efficacy and self-regulation would enable an individual to set high goals and positively regulate one's behaviour towards the goal, making it more likely for one to achieve it. Therefore, high self-efficacy and self-regulation is necessary to enable a positive behaviour change.

## 4.2 Video Self-modelling

Modelling is the process of imitating actions and behaviour based on observational learning [22, 25, 26]. According to Badura, modelling entails observing a subject in order to obtain knowledge about a certain skill. This observed information is

then tried out and maintained using cognitive representation when they venture the replication of the skill. Modelling can be implemented by showing video clips of themselves or others performing the activity.

This is called video modelling. Video modelling that involves using self-models is referred to as video self-modelling. A meta-analysis by Bellini et al. [38] tested the intervention, maintenance, and generalization effects of video modelling and video self-modelling interventions in twenty-three studies published between 1987 and 2005 for children and adolescents with autism spectrum disorders. Results imply that video modelling and video self-modelling are effective intervention strategies for addressing social-communication skills, functional skills, and behavioural functioning in children and adolescents with autism spectrum disorders.

A study by Krouse [203] used video modelling to educate patients about changes in health care delivery. They examined 18 research studies involving video modelling. In spite of differences in research designs, clinical settings, and patient populations the use of video modelling has potential benefits for clinical practice in facilitating knowledge acquisition, reducing preparatory anxiety, and improving self-care. Baudry et al. [35] investigated the effectiveness of video modelling in improving gymnasts' performance of the circle on a pommel horse. The modelling group received expert- and self-modelling, and performance feedback. The control group received no feedback. The results showed better performance in the modelling group than the control group. This shows that video modelling has potential in improving complex sports movements such as the double leg circle on the pommel horse.

Resemblance to the model increases self-efficacy because learners are able to identify more with the model [160]. Self-modelling uses a model of an individual achieving a goal to induce higher motivation and learning of the behaviours required to achieve that goal [98]. Self-modelling is more effective than using peer models [99, 219, 308]. Starek et al. [310] compared the effects self-modelling and other-modelling which refers to watching a video tape of a peer model that exhibits skills matching the player's swimming skills. Results showed participants in the self-modelling condition exhibited better performance than the ones in the other-modelling condition.

## 4.3 Feedforward

Feedforward is a psychophysical training technique which enables individuals to achieve a rapid improvement in performance by observing an enhanced self-model showing previously unachieved performance introduced by Peter Dowrick [99]. Dowrick [99] explains this ultrarapid learning in feedforward within the framework of cognitive science using the neural activity called "mental time travel" [134,314]. Mental time travel which is also referred to as autonoetic consciousness [335] enables remembering the past and projecting or imagining the future. It gives us the ability to build a sense of self.

Future or past episodic memory is responsible for self-awareness, and intrinsic feelings that may impact our future actions [15] by allowing people to predict, architect, and sculpt future events [314]. A similar process called prospection is defined as the act of thinking about the future by mentally projecting ourselves into an imagined situation. Buckner et al. [57] suggest that "envisioning the future (prospection), remembering the past, conceiving the viewpoint of others and possibly some forms of navigation reflect the workings of the same core brain network". They claim that all these abilities share the same functional anatomy that includes frontal and medial temporal systems that are conventionally related to planning, episodic memory and passive cognitive states. Dowrick explains that self-modelled feedforward is an application of prospection or future mental time travel and it trigger a behavioural response in a future context [99]. In addition to mental time travel, Dowrick attributes the rapid learning to the activation of mirror neurons which are responsible for behaviour imitation during the process of feedforward [99].

In feedforward, the self-model is created (usually by selective video editing) to exhibit an improved performance that has not yet been consistently achieved. It enables existing component behaviours to "become reconfigured as future 'new' skills or placed in a new or challenging context" [100]. It is conjectured that self-modelling may be based on the activation of mirror neurons, i.e. the self-model activates the neural circuits responsible for the modelled behaviour. The more similar a model is to an individual, the better it is able to activate the relevant mirror neurons; therefore, a self-model is better suited for feedforward than an

‘other’ model such as a video recording of another individual.

Feedforward effects have been reported for a number of learning, treatment and training applications [100], including applications in sports and exercise such as football [311] and power-lifting [123]. In a study comparing self-modelling with ‘other’ (i.e. non-self) modelling in beginner swimmers, players in the self-modelling condition demonstrated better performance [310]. A case study of self-modelling for a professional mountain biker identified benefits including improved motivation, confidence, and concentration [331].

Clark et al. [71] compared two self-as-a-model interventions: enhanced self-modelling or feedforward which involved watching edited videos showing only the best performances of swimming stroke and self-observation of performance at their current skill levels. They studied the influence of the modelling interventions on self-regulation, intrinsic motivation, self-efficacy, and the physical performance. The results showed that the feedforward group consistently performed better in terms of self-regulation, self-efficacy, intrinsic motivation, and physical performance than the self observation group. A study by Gilchrist et al. [135] investigated alleviating public speaking anxiety by using enhanced self-modelling or feedforward. Players were shown edited videos of themselves depicting confident speaking. Results showed video-self-modelling could be used as an intervention to reduce anxiety and improve public speaking performance.

A study of competitive trampolinists found that players used feedforward to improve their performance, with potential benefits including improved self-efficacy and motor execution [342]. These works used a static feedforward stimulus that was passively consumed, such as a video. The closest in topic and spirit to my work is a study by Gonzales et al. [139] where athletes running on a treadmill were asked to match (not surpass) a video of themselves running at an optimal stride. With the video they achieved longer performances before they suffered from exertion and lower oxygen consumption. My aim is to elicit an interactive feedforward effect by using a self-model which serves as a competitor, as opposed to a non-interactive video. I call this *interactive feedforward* because individuals actively interact with their self-model in real-time in a VR feedforward experience as opposed to passively observing their self-model. This is related to the practice of

setting challenges or targets; however, the target is presented through a self-model rather than using typical targets without reference to self.

## 4.4 Summary

Feedforward enhances intrinsic motivation, self-efficacy, self-regulation, and performance [71]. Therefore, feedforward could be potentially useful in improving exercise behaviour leading to exercise adherence. VR exergaming can be coupled with feedforward to create a potentially more powerful exercise intervention. This can be achieved by recording a player's performance to create a self-model. This can be programmatically enhanced to create an enhanced self-model which exhibits previously unachieved performance levels. The enhanced self-model can then be used as a competitor in the VR exergame.

# Chapter 5

## Interactive Feedforward in High Intensity VR Exergaming

*“You must expect great things of yourself before you can do them.”*

---

*Michael Jordan*

### 5.1 Introduction

High Intensity Interval Training (HIIT) – short intermittent bouts of vigorous activity, interspersed with periods of rest or low-intensity exercise [131] – can reduce the time required for a healthy exercise regime. Studies show that HIIT is equally beneficial or superior to traditional aerobic exercise in many fitness and health related measures [132, 206, 259]. Players also enjoy it more and prefer it to longer, lower intensity aerobic exercise [33, 330]. However, it remains a challenge to motivate people to exercise at sufficient intensity [120, 264] and maintain a regime of vigorous exercise [51, 261].

There is evidence that exergames increase enjoyment and intrinsic motivation compared to conventional exercise and distract from uncomfortable bodily sensations [16, 27, 117, 238, 301]. Exergames can be effective in motivating players to exercise at light-to-moderate intensity [16, 145, 238, 269]. There is some evi-



dence that exergaming also holds promise for motivating exercise at a high intensity [146,195,236,362]. However, motivating players to work at high intensity in an exergame remains a challenge, as hard exercise often reduces pleasure [41,108,268].

I propose to improve a player’s exercise performance in a VR HIIT exergame while maintaining intrinsic motivation using an *interactive feedforward* method. Feedforward is an established method to help an individual learn or improve a skill or performance, “in which an image of success is constructed to illustrate achievement beyond the individual’s current ability” and which can result in “remarkably rapid changes of behaviour and improvements of performance” [98]. Feedforward is a type of *self-modelling*, an intervention procedure using recordings of oneself engaged in adaptive behaviour to learn skills or adjust to challenging environments as part of a training or therapy protocol [97].

To improve performance with feedforward, two conditions must be met: 1) a self-model of an individual must be “constructed”, usually by editing videos, to create essentially a future image of improved behaviour, and 2) the individual should see themselves in a desired performance. Dowrick suggests that an enhanced self-model may serve not only as a model to which you aspire but as a competitor to elicit improvement in performance [98]. The interactive feedforward method is the first to use an enhanced self-model as a competitor in this way. 1) a self-model of an individual exhibiting the desired performance must be constructed (typically in the form of a video recording), the individual identifying with the self-model, and 2) the performance of the self-model should appear markedly improved compared with the individual’s current ability; that is, a future, desired performance. The dynamic behaviour of an enhanced interactive self-model can only be effectively simulated in a virtual environment.

My exergame and setup using a stationary exercycle and head-mounted display (HMD) are shown in Figure 5-2. In order to create a self-model, I recorded the player performing an exergame session on the bike. I then replayed this recording as a self-model in subsequent HIIT sessions in the form of a “ghost” avatar so the players compete against their own previous performance. In a videogame context, the term “ghost” refers to a self-model moving at the pace of a player’s previous performance. For the self-model to function as markedly improved, I increased

the bike resistance while players raced against the self-model. Thus, the effort required to outrace or maintain the same pace as the ghost was higher due to the increase in resistance of the exercise bike. I call this *interactive feedforward* as, in contrast to how feedforward is typically used, individuals are not merely passive recipients of a self-model (e.g. in the case of a video [101]) but interact with it in real-time in a VR feedforward experience. This is related to the practice of setting challenges or targets; however, the target is presented through a self-model rather than using typical targets without reference to self. I hypothesise that interactive feedforward, in which players identify with the self-model while perceiving it as performing at a level they have not previously achieved, will improve performance more than an unenhanced self-model [78, 300, 353]. I operationalise performance as average power output, which is a measure of performance widely used in sport and exercise science.

Ideally, I would like my method to increase both performance and intrinsic motivation. However, this goes against human psychophysiological constraints, which have been shown to reduce positive affect as physical exertion nears or surpasses the ventilatory threshold [108] which is characterised by a disproportionate increase in ventilation with respect to oxygen consumption [168]. I cannot change the fact that vigorous exercise feels ‘hard’, therefore, it is unrealistic to expect interactive feedforward to improve performance while significantly *increasing* intrinsic motivation. It is plausible, however, that good exergame design can mitigate loss of intrinsic motivation [117, 119, 278, 301]. Hence, I hypothesise that interactive feedforward will not be significantly worse than an unenhanced self-model in its effect on intrinsic motivation. To test this, I use *non-inferiority testing* [209, 297], which is widely used in clinical trials but has hardly been used in HCI. It tests whether a method is not worse than a justifiable margin compared to a known method. The non-inferiority margin was selected based on the results of other studies using the Intrinsic Motivation Inventory (IMI) Interest/Enjoyment subscale, considering differences in IMI scores that were meaningful with regard to a context or treatment [70, 119, 174, 228, 278].

Interactive feedforward can be regarded as a suitable method for performance improvement in exergames only if players are aware it is being used. Evidence suggests that in traditional exercise participants employ pacing strategies that leave

a significant metabolic energy reserve at the end of exercising [316]. Researchers have attempted to access this reserve by influencing participants' pacing strategy in continuous exercise through deceptive performance feedback, with equivocal results [185]. Challenging athletes with pace-setters based on previous performance levels is an established method for improving performance in traditional sports and exercise. However, it is unclear how far deception and the perception of a challenge contribute to these improvements [186, 187, 303, 353]. It is impractical and potentially unethical to count on players' ignorance in the long term. Users are likely to notice marked changes in intensity as they play an exergame. When using feedforward with video, individuals are usually involved in the creation of the self-modelling video and hence fully aware of the method [98, 100, 101]. Therefore it was also important to investigate whether awareness of resistance increase in an exergame compromised its efficacy.

My concept of interactive feedforward is based on competition against a self-model ("self-competition"). This is different from competition against a virtual competitor ("non-self-competition") which is widely used in racing games. Feedforward theory [98] and empirical evidence [310] suggest that self-models are more powerful than models of others, as participants are able to identify and relate more closely to self-models. Furthermore, there is evidence to suggest that competition against others can have a detrimental effect on intrinsic motivation, especially in less fit individuals [89, 276]. Therefore it was also important to investigate whether interactive feedforward not only improves an individual's performance more than competition against a virtual non-self-competitor but is also more effective in intrinsically motivating players. In summary, I investigated the following research questions:

- RQ1** How effective is interactive feedforward in improving performance as measured by average power output while maintaining intrinsic motivation?
- RQ2** How robust are the effects of interactive feedforward to a player's awareness that the method is being used?
- RQ3** How do interactive feedforward and non-self competition differ in terms of performance and intrinsic motivation?

Self-modelling and feedforward have mostly been used with video (“video self-modelling”) [71, 98, 100, 101, 123, 310, 311, 331, 342]. To my knowledge, feedforward has never previously been used in interactive exergaming. Therefore, the following are contributions to this field of research:

1. An exergame implementing interactive feedforward in virtual reality.
2. An empirical study investigating the efficacy of interactive feedforward in improving physical performance while maintaining intrinsic motivation in my exergame.
3. An investigation of the robustness of the approach with regard to a player’s awareness of the method being used.
4. A comparison of self competitive interactive feedforward and competition with others.

## 5.2 Experiment I: Interactive Feedforward

### 5.2.1 Exergame Design

My exergame is a VR racing game played riding a computer-controlled stationary exercycle and wearing an HMD; see Figure 5-2. The exercycle was a Lode Excalibur Sport. The HMD was an HTC Vive. Both were connected to a PC running Unity with an Intel Xeon E5 2680 processor, 64 gigabytes of RAM, and two NVIDIA Titan X graphics cards running in SLI mode. The game was designed by Whalley [347] based on the principles outlined by Shaw et al. [302]. I reverse engineered the Lode Excalibur Sport exercise bike to make it inter-operable with the game using the serial port interface. In order to provide a systematic overview, I describe the game along the dimensions of the frequently used MDA model (Mechanics, Dynamics, and Aesthetics) [172].

#### **Mechanics:**

The player cycles along a straight road while avoiding slow moving trucks. In the game, the player’s bike is always facing forward to avoid VR sickness due to sensory disconnect [47, 302]. In-game speed is proportional to the current pedalling cadence (in RPM) measured by the exercycle sensors. The player can



Figure 5-1: The self-modelling cue

move laterally by leaning her head left and right; the speed of lateral movement is proportional to the roll angle measured by the HMD sensors.

### **Dynamics:**

The gameplay follows a HIIT protocol as shown in Figure 5-3, starting with a warm-up, followed by a number of high-intensity sprints separated by recovery phases, and finishing with a cool-down. The number of sprints, the resistance (exercycle breaking torque) and duration of each phase are configurable. During warm-up, recovery, and cool-down, the resistance is low and the main gameplay objective is to avoid trucks, which are moving straight along the road. During sprints, the resistance is high and the main gameplay objective is to cycle as fast as possible. Trucks are still present but more sparsely placed. In case of a collision with a truck, the truck simply disappears without further consequence to avoid disrupting the flow of the exercise protocol and thereby to preserve the intensity of HIIT. During gameplay, the distance to the ghost, a countdown for the time remaining in the current phase and the current RPM are shown. Four seconds before a sprint starts, a message “get ready to sprint!” is displayed at the

centre of the HMD. Rear-view mirrors were added to the bike in the exergame so that if the player overtakes their self-model they can still see the self-model in the mirrors to add a sense of competition. The exergame is scalable to the ability of the individual in order to impose a level of challenge that is close to optimal which is more engaging, immersive and increases the chances of entering the state of flow [83, 182].

### **Aesthetics:**

According to Adzei et al., the hot and warm colours create the illusion of excitement and agitation while the cool and cold colours create the illusion of peace [5]. The low-intensity phases (warm-up, recovery, cool-down) aim to evoke a relaxed mood, using a sunny scene, blue sky, and a bright colour palette (Figure 5-4). For the sprints, there is a transition to a night time scene with street lamps beside the road and police cars with flashing red emergency lights following the player, to evoke a sense of pressure and urgency (Figure 5-5). Players were told that they had to out-run the police prior to the start of the experiment.



Figure 5-2: Exergame Setup

Competition Framing	Resistance Awareness	Game Mode (within-participant)		
		Baseline (B)	Equal Challenge (E)	Harder Challenge (H)
Self (SC)	None (NA)	Record self-model	Replay self-model + self cue	Improved self-model + self cue (IFF)
	Vague (VA)	Record self-model	" + "may change intensity"	" + "may change intensity"
	Full (FA)	Record self-model	Replay self-model + self cue	" + "will be harder"
Non-Self (NSC)	None (NA)	Record "competitor"	Replay "competitor", no cue	Improved "competitor", no cue

Table 5.1: Experimental design overview. I call condition SC+H the “Interactive FeedForward” (IFF) condition.

### Incorporating Feedforward

The exergame can be played in three different game modes. In the *Baseline* mode (B), the player’s movements are recorded while they complete the configured HIIT protocol. Hence, this mode can be used to create a self-model. In the *Equal challenge* mode (E), a self-model previously obtained in mode B is played back in the form of a “ghost” avatar, similar to [300]. This allows players to compete against themselves (“Self Competition”), resulting in a challenge equal to one of their previous performances. To reinforce that the “ghost” represents a self-model, a short “self-model cue” animation sequence is played at the beginning of mode E, showing the ghost with a message “This is you” in the centre of the HMD (Figure 5-1). At the beginning of each sprint, the game adjusts the positions so that player and avatar start sprinting next to each other. Even if player or avatar fall behind in one of the sprints, they start the next sprint on an equal footing.

The *Harder challenge* mode (H) is designed to elicit a feedforward effect. It is the same as mode E except that the resistance is increased by a constant factor. With this increase, the ghost serves as an improved self-model, requiring a performance that has not yet been achieved, as the effort required to maintain the same pace as the ghost increases with the resistance. In contrast to typical video self-modelling, where the feedforward stimulus is passively consumed simply by viewing it, this mode provides an interactive feedforward experience where the player competes with the improved self-model.

### 5.2.2 Experimental Design

**RQ1: How effective is interactive feedforward in improving performance and retaining enjoyment?**

I investigated the effectiveness of interactive feedforward in improving performance

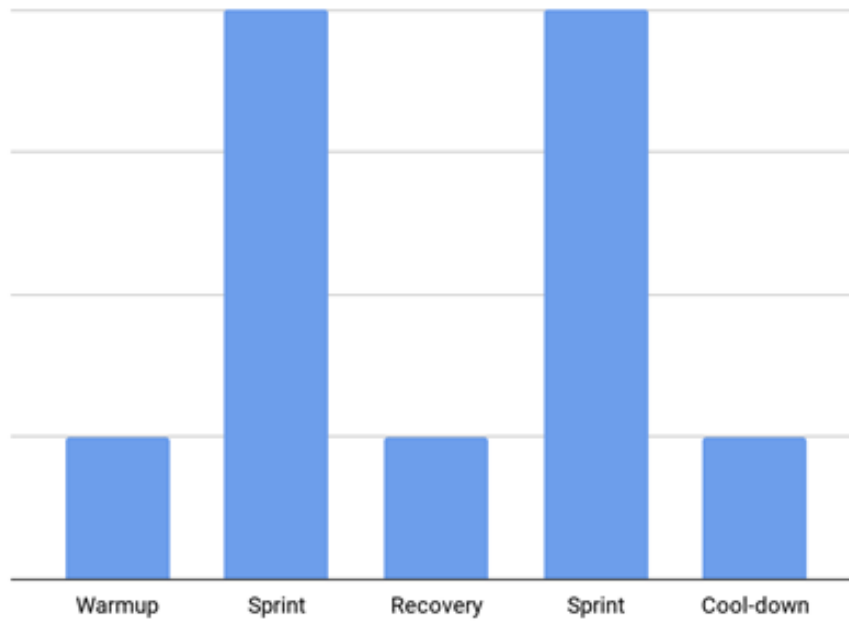


Figure 5-3: High Intensity Interval Training



Figure 5-4: Low Intensity Phase (daylight graphics displayed during warm up, recovery, and cool down phases)





Figure 5-5: High Intensity Phase (night-time graphics displayed during sprint phases)

and maintaining intrinsic motivation (RQ1) using a within participants design for the independent variable *game mode* with levels Baseline (B), Equal challenge (E), and Harder challenge (H). Players started with B to create a self-model of their performance and in E players were asked to compete with their self-model. In H I attempted to elicit a feedforward effect by, in addition to competing with the self-model, increasing the resistance by 10%. This value was chosen because it is a meaningful increase in exercise intensity and was likely still achievable for many players based on pilot testing. The order of E and H was counterbalanced. Other studies did not detect any performance differences between self competition and a baseline [300, 353], suggesting that performance in E and B will be similar. Therefore, I focused on comparing performance improvement relative to B and intrinsic motivation in E vs. H.

**RQ2: How robust is interactive feedforward with regard to a user’s awareness of the method?**

In order to determine if the interactive feedforward effect is robust with regard to a user’s awareness of the method of increasing resistance (RQ2), I used a between participants design for the independent variable *resistance awareness* with levels

No Awareness (NA), Vague Awareness (VA), and Full Awareness (FA). Each of the three groups followed the repeated measures design of B, E, H described above. For NA, players were not told about the increased resistance in H, although it was likely that they would feel it. For VA, a message was displayed at the beginning of every game mode condition stating “The exergame may change the intensity of the workout to make it easier or harder”. For FA, I displayed the message “The exergame will be made harder” before condition H. I compared performance and intrinsic motivation across the different levels to investigate if increasing awareness of the increased resistance influenced the effectiveness of the feedforward method in improving performance while maintaining intrinsic motivation.

**RQ3: How is interactive feedforward different from non-self competition?**

To investigate differences between the feedforward effect elicited by self competition and competition with others (RQ3), I used a between participants design for the independent variable *competition framing* with levels Self Competition (SC) and Non-Self Competition (NSC). Each group followed the same repeated measures design of B, E, H. For SC, the competition in E and H was framed as self competition, i.e. players were informed that they were competing against a recording of their performance in B. I refer to SC+H as the interactive feedforward condition. For NSC, the competition in E and H was framed as competition with others. Players of the NSC group were informed that they were competing against a “virtual competitor” before the experiment started. Players of the SC group were informed that they were competing with a self-model before the experiment started. The virtual competitor was their own recording of B, exactly as in SC, but players were not aware of this. Apart from the framing, the only difference from SC was that in NSC the self-model cue was not shown. Players were not told that the exercycle’s resistance would be increased in NSC+H, i.e. no awareness (NA). Awareness of the resistance is less relevant in the context of NSC because, in contrast to SC, no expectations are set by a self-model. The NSC group was compared with group SC+NA with regard to performance improvement (relative to B) and intrinsic motivation.

The overall study design is summarised in Table 5.1. I have four groups: SC+NA, SC+VA, SC+FA, and NSC+NA. Each group uses a within participants design for

game mode (B, E and H) with counterbalanced order of E and H (after recording in B). Players were randomly assigned to the groups, with 12 players per group.

### Outcome variables

To measure players' exertion based on Heart Rate (HR), I used a Polar H10 chest strap sensor. For each condition, the mean of the peak HRs of the two sprints was calculated and expressed as a percentage of a player's estimated maximum HR (HR Peak%). Based on ACSM guidelines [262], maximum HR was estimated as 220 minus age. This measure is commonly used in exercise studies to confirm players are working at a required level of exertion. As a measure of performance, I recorded the average power output (Power) in Watts over both sprint phases in each condition, as measured by the exercycle sensors. To compensate for differences in physical fitness between players, I considered each player's performance in the E and H game mode against their baseline B, i.e.  $\text{Power}_{E-B}$  and  $\text{Power}_{H-B}$ , which I refer to as  $\Delta\text{Power}$  in the context of game mode E or H.

To measure intrinsic motivation, I used the Intrinsic Motivation Inventory (IMI) scale [288], which has been used and validated for sports and exercise [70, 225]. The IMI comprises seven subscales, but only the Interest/Enjoyment subscale measures intrinsic motivation and is considered the main self-report measure. I therefore, focused on the Interest/Enjoyment subscale, while also considering the Pressure/Tension subscale, which is a negative predictor of intrinsic motivation. The scores are on a scale from 1 to 7, with 7 representing the highest intrinsic motivation or pressure/tension respectively [91]. To measure flow, I used the Flow State Questionnaire of the Positive Psychology Lab (FSQ) [216], which has been validated with exergames. It has two subscales: Balance of Challenges and Skills, and Absorption in the Task. I recorded the subscale scores as averages over all item scores between 1 and 5, with 5 representing the highest level of flow. I used the Immersive Experience Questionnaire (IEQ) [182] to quantify how immersive the exergaming experience was. The IEQ has been used widely in ludology, including for exergames [61]. I recorded the IEQ score as an average over item scores between 1 and 7, with 7 representing the highest level of immersion.

## Exercise Protocol

A low-volume HIIT protocol suits my exergame particularly well: besides its wide applicability, appeal, and health benefits, the short format mitigates typical HMD usability problems such as VR sickness, sweat and wearer discomfort [302]. Based on ACSM guidelines for exercise [262] and related work [131, 176, 231], I used the following protocol: 60 sec warm-up, 30 sec sprint, 90 sec recovery, 30 sec sprint, 90 sec cool-down.

## Resistance

In the warm-up, recovery, and cool-down phases, players were instructed to cycle at a low cadence, between 65 and 70 RPM, with a low resistance of 12 Nm. The resistance during sprints was initially set to  $0.4 \text{ Nm kg}^{-1}$  based on a player’s body mass, which is in line with the resistance used for other low-volume Wingate-style protocols [176]. It was then adjusted, if necessary, for each player in a familiarisation phase based on feedback, to enable them to perform at a “very hard” rate of perceived exertion (RPE) during all sprints while avoiding uncontrolled movements due to high cadence.

## Hypotheses

Based on related work and pilot trials, I had the hypotheses:

- H1** Interactive feedforward (SC+H) improves performance as measured by average power output compared to competition against a non-improved self-model (SC+E) (RQ1).
- H2** Interactive feedforward (SC+H) improves performance in all awareness conditions (NA, VA, FA) (RQ2).
- H3** Interactive feedforward (SC+H) improves performance compared to competition with others (NSC+H) (RQ3).
- H4** Interactive feedforward (SC+H) is not inferior in its effect on intrinsic motivation compared both to no competition (SC+B) and to competition with a non-improved self-model (SC+E) (RQ1).
- H5** Interactive feedforward (SC+H) improves intrinsic motivation compared to

Competition Framing	Resistance Awareness	n	Demographics	Variable	Game Mode (within-participant)		
					Baseline (B)	Equal (E) Challenge	Harder (H) Challenge
Self (SC)	None (NA)	12	m=9, f=3 age=23±4 IPAQ=2664±1924 MET IEQ=5.74±0.65	HR Peak%	84.61±8.77	87.09±8.84	88.71±8.42
				Power	325.15±76.46	344.52±92.02	378.46±93.26
				ΔPower		19.37±23.19	53.31±26.03
				IMI Enjoyment	5.76±1.02	6.18±0.93	6.06±0.75
				FSQ Balance	4.12±0.65	3.98±0.75	4.00±0.67
				FSQ Absorption	4.13±0.59	4.19±0.65	4.30±0.50
	Vague (VA)	12	m=12, f=0 age=30±7 IPAQ=4354±2195 MET IEQ=5.34±0.46	HR Peak%	83.01±9.99	86.65±8.06	86.82±7.73
				Power	370.09±76.23	395.47±70.85	417.40±71.95
				ΔPower		25.38±28.81	47.32±32.86
				IMI Enjoyment	5.34±1.06	5.43±1.20	5.33±1.42
				FSQ Balance	4.12±0.45	4.01±0.69	3.77±0.94
				FSQ Absorption	3.71±0.45	3.81±0.60	3.63±0.52
	Full (FA)	12	m=7, f=5 age=31±9 IPAQ=2213±1102 MET IEQ=5.41±0.63	HR Peak%	84.39±9.35	87.40±9.14	87.75±9.45
				Power	309.44±92.17	312.64±92.75	340.07±92.25
				ΔPower		3.20±11.93	30.63±25.94
				IMI Enjoyment	5.98±0.69	5.70±0.89	5.60±0.93
				FSQ Balance	4.12±0.56	4.17±0.46	3.77±0.77
				FSQ Absorption	3.79±0.50	3.97±0.71	3.71±0.75
Non-Self (NSC)	None (NA)	12	m=7, f=5 age=27±6 IPAQ=2754±1176 MET IEQ=5.02±0.86	HR Peak%	85.09±6.20	88.75±5.52	87.34±5.12
				Power	267.16±80.35	274.77±84.42	289.50±93.45
				ΔPower		7.61±19.03	22.34±21.49
				IMI Enjoyment	5.25±1.06	5.21±0.91	4.58±1.08
				FSQ Balance	3.57±0.80	3.49±0.54	2.97±0.86
				FSQ Absorption	3.65±0.67	3.91±0.62	3.77±0.72

Table 5.2: Summary of demographics and results for Experiment-I (mean ± std. dev.).

competition with others (NSC+H) (RQ3).

### 5.2.3 Procedure

Players answered the questionnaires on a PC next to the bike. They got off the bike and were provided with a chair. Players were screened using the Physical Activity Readiness Questionnaire (PAR-Q) [326]. If a player answered ‘yes’ to any of the PAR-Q questions or had a resting blood pressure greater than 140/90 mmHg, they were excluded from doing the experiment. Players were then asked to complete pre-experiment questionnaires including a demographics questionnaire and the International Physical Activity Questionnaire (IPAQ) [147]. Demographics questionnaire included questions about age, gender, blood pressure, body height, weight, body composition, and number of exercise hours. They were given a choice of male/female/other for gender. The IPAQ estimates the volume of physical activity in Metabolic Equivalent of Task (MET) units for each group as shown in Table 5.2. Players were asked to read an instruction sheet about the experiment with details about the exergame, the exercise protocol and the experiment. The instruction sheet stated either that players would race against a recording of their own previous performance (SC) or against a “virtual competitor” (NSC). Players were instructed to work very hard during the sprints and to maintain 65-70 RPM during the low-intensity phases. After initialising sprint resistance based on body mass, players went through a familiarisation phase which allowed them to experience the full 5-minute protocol in the exergame and adjust the sprint resistance to their level of fitness. Players then played the exergame in each of the three game modes, in the order BEH or BHE, with cues shown according to their resistance awareness and competition framing group. After each of the three conditions, players were asked to complete the IMI, FSQ and leave comments on their experience as qualitative feedback. Players had a break of about 10 minutes between the gameplay rounds to avoid fatigue. They were allowed to take longer breaks if they were feeling tired. At the end of the experiment players were asked to complete the IEQ. The experiment took about 75 minutes.

## Participants

I recruited 54 players (35 males, 13 females; age 18-51, mean 28) through mailing lists and posters. They were a mixture of students and employees of the University of Bath. Six players were excluded or discontinued the experiment because of high blood pressure (2), fatigue (2), VR sickness (1) or eye defects (1). All others were randomly assigned to one of the four groups, with 12 players per group. All players gave written, informed consent and were remunerated for their time. Players were handed £10 Amazon vouchers at the end of the experiment.

## 5.2.4 Results

### Assumptions for Statistical Methods

The conditions that were compared had the same number of samples (12), for each dependent variable the variances within each condition were close enough to equal (homoscedastic) and the measurements' distributions close enough to normal to warrant an analysis of variance (ANOVA). In cases where Mauchly's test indicated a violation of sphericity for a repeated measures ANOVA, Huynh-Feldt correction was used. I used the  $\omega^2$  measure for ANOVA effect sizes [263], and all instances of 'significant' refer to 'statistically significant', taking a significance level of  $\alpha = .05$ .

### Non-inferiority Methodology

The non-inferiority hypotheses were tested following the Confidence Interval (CI) approach, which is recommended practice for non-inferiority trials [209, 297]. A non-inferiority margin  $d$  was specified, which is the maximum tolerable difference between an 'old' and a 'new' treatment for the new treatment to be considered non-inferior. In my case, the 'old' treatments are B and E, and the 'new' treatment is H. If the two-tailed 95% CI of the mean difference between the treatments lies above  $d$ , then the new treatment is considered non-inferior. I chose a non-inferiority margin  $d_{Enjoy} = -0.3$ , based on reported characteristics of the IMI [70, 119, 174, 228, 278] which support the assumption that differences smaller than 0.3 points on the 7-point IMI Interest/Enjoyment scale are tolerable for non-inferiority.

### Overview

A summary of the results is shown in Table 5.2. The results are illustrated in

Figures 5-6 and 5-7, showing means with 95% CIs. HR Peak% is on average above 80 in all conditions, which indicates that players were exercising to the required intensity for HIIT [262]. Independent-samples t-tests were conducted to compare all measurements made in game modes E and H between the two counterbalanced order groups, BEH and BHE. There were no significant order effects, all  $|t| \leq 1.31, p \geq .20$ .

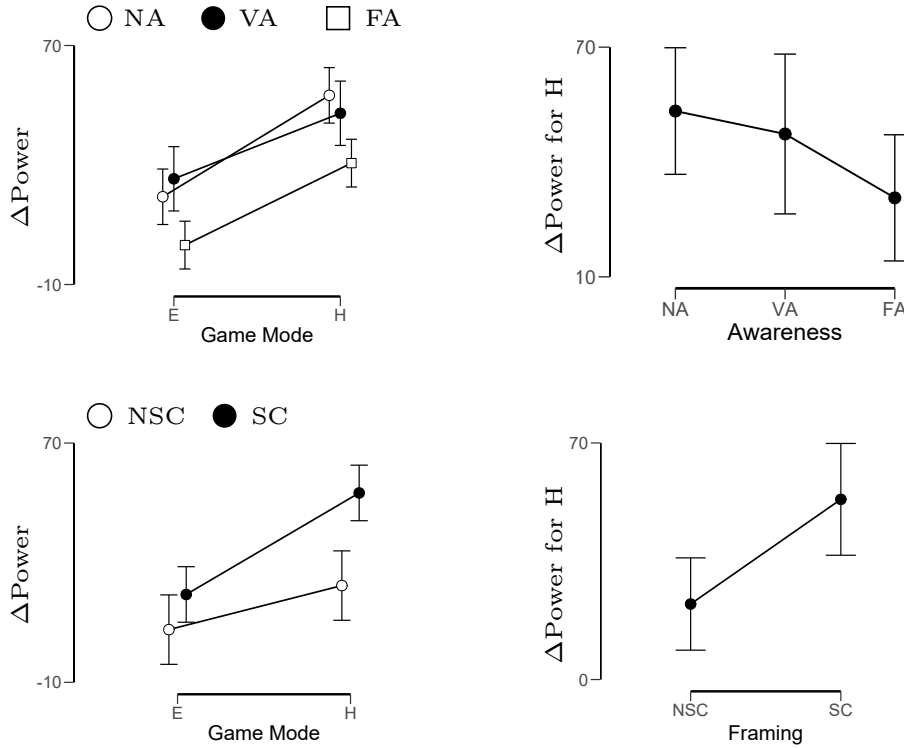


Figure 5-6:  $\Delta$ Power (difference from baseline B) for the equal challenge (E) and harder challenge (H) conditions in different levels of resistance awareness (top-left) and in non-self (NSC) vs. self competition (SC) framing (bottom-left).  $\Delta$ Power for H in different levels of resistance awareness (top-right) and competition framing (bottom-right).

# **H1: Feedforward improves performance more than self-competition (RQ1).**

A two-way repeated measures ANOVA was conducted on the effects of game mode (E and H) and resistance awareness (NA, VA and FA) for self competition



(SC) on the average power output increase from baseline  $\Delta\text{Power}$  (Figure 5-6 top-left). The main effect of game mode was significant,  $F(1, 33) = 63.2, p < .001$ , indicating that the harder challenge mode in self competition (SC+H) improved performance more than the equal challenge mode in self competition (SC+E) with a ‘large’ effect size ( $\omega^2 = 0.63$ , 95% CI of Cohen’s  $d$  [0.88, 1.80]). This indicates that the feedforward effect was elicited in the SC+H condition and that it resulted in improved performance, therefore, I accept H1. The main effect of awareness,  $F(2, 33) = 2.76, p = .08$ , and the interaction effect,  $F(2, 33) = 0.99, p = .38$ , were not significant. A dependent-samples t-test comparing Power for B and E in SC showed that there was a significant difference between B and E,  $t(35) = 4.04, p < .001$ , with a ‘medium’ effect size (Cohen’s  $d=0.67$ ).

**H2: Awareness of feedforward does not compromise performance improvement, i.e. in all awareness conditions feedforward leads to an improvement in performance (RQ2).**

A one-way ANOVA showed that the effect of resistance awareness (NA, VA, FA) on  $\Delta\text{Power}$  in H ( $\text{Power}_{H-B}$ ) was not significant,  $F(2, 33) = 2.05, p = .15$  (Figure 5-6 top-right). Independent-samples t-tests of the marginal means with Bonferroni correction showed that  $\text{Power}_{H-B}$  was significantly positive for all levels, NA ( $t = 6.49, p < .001$ , 95% CI [32.59, 74.03]), VA ( $t = 5.76, p < .001$ , 95% CI [26.59, 68.04]) and FA ( $t = 3.73, p = .002$ , 95% CI [9.91, 51.36]). That is, in all awareness conditions feedforward (SC+H) led to a significant improvement in performance compared to baseline, so I accept H2.

**H3: Feedforward improves performance compared to competition with others (RQ3).**

A two-way repeated measures ANOVA was conducted on the effects of game mode (E and H) and framing (SC and NSC) for no awareness (NA) on the power increase from baseline  $\Delta\text{Power}$  (Figure 5-6 bottom-left). The main effect of game mode was significant,  $F(1, 22) = 25.97, p < .001$ , indicating that a harder competitive challenge increased performance more than a challenge equal to baseline with a ‘large’ effect size ( $\omega^2 = 0.47$ , 95% CI of Cohen’s  $d$  [0.49, 1.49]). The main effect of framing was significant,  $F(1, 22) = 7.34, p = .01$ , indicating that self competition increased performance more than non-self competition with a ‘large’ effect size ( $\omega^2 = 0.21$ ). The interaction effect was not significant,

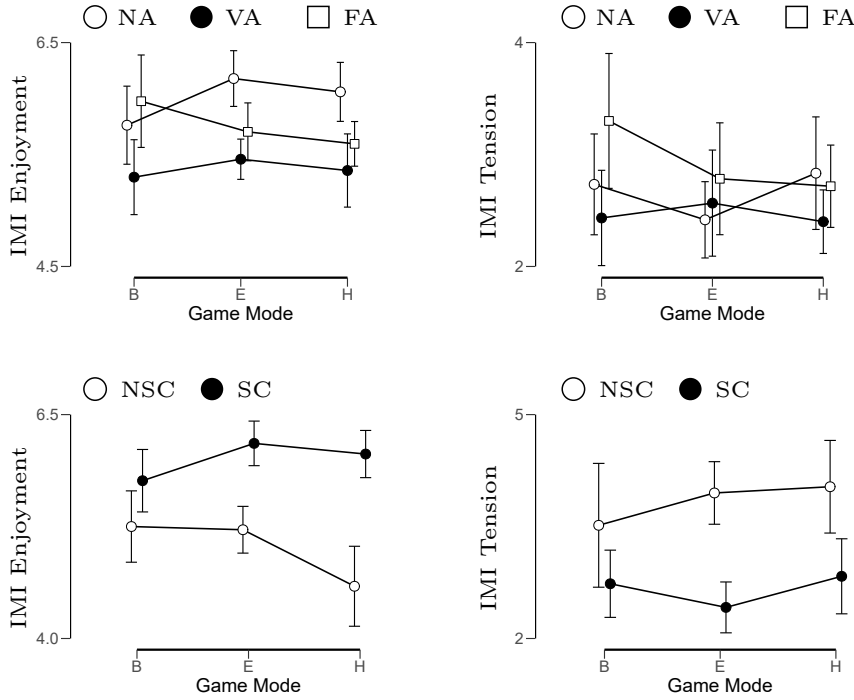


Figure 5-7: IMI Interest/Enjoyment (left column) and IMI Pressure/Tension (right column) scores for the baseline (B), equal challenge (E) and harder challenge (H) conditions for 1) self competition (SC) framing in different levels of resistance awareness (top row) and 2) without resistance awareness (NA) in self competition (SC) vs. non-self competition (NSC) framing (bottom row).

$F(1, 22) = 4.05, p = .06$ . An independent-samples t-test comparing  $\text{Power}_{H-B}$  for SC and NSC (Figure 5-6 bottom-right) showed that SC led to a significantly higher performance,  $t(22) = 3.18, p = .002$ , with a ‘large’ effect size (Cohen’s  $d=1.30$ ), so I accept H3.

**H4: Feedforward is not inferior with regard to its effect on intrinsic motivation compared to non- and self-competition (RQ1).**

A two-way repeated measures ANOVA with Huynh-Feldt correction was conducted on the effects of game mode (B, E and H) and resistance awareness (NA, VA and FA) for self competition (SC) on IMI Interest/Enjoyment scores (Figure 5-7 top-left). The main effect of game mode,  $F(1.57, 51.96) = 0.62, p = .51$ , the main effect of awareness,  $F(2, 33) = 1.45, p = .25$ , and the interaction effect,

$F(3.15, 51.96) = 2.24, p = .09$ , were not significant. The 95% CI of the mean difference between B and H was  $[-0.28, 0.26]$  (i.e. likely at most 0.28 higher interest/enjoyment in B); the 95% CI of the mean difference between E and H was  $[-0.25, 0.04]$  (i.e. likely at most 0.25 higher interest/enjoyment in E). In both cases the lower bound is above  $d_{Enjoy} = -0.3$ , indicating that the feedforward effect elicited in SC+H does not worsen, within the specified non-inferiority margin, intrinsic motivation compared to no competition in the baseline mode (SC+B) and self competition in the equal challenge mode (SC+E). Therefore, I accept H4. A two-way repeated measures ANOVA was conducted on the effects of game mode (B, E and H) and resistance awareness (NA, VA and FA) for self competition (SC) on IMI Pressure/Tension scores (Figure 5-7 top-right). The main effect of game mode,  $F(2, 66) = 1.06, p = .35$ , the main effect of awareness,  $F(2, 33) = 0.82, p = .45$ , and the interaction effect,  $F(4, 66) = 1.36, p = .26$ , were not significant.

Independent-samples t-tests with Bonferroni correction were conducted to test whether the IMI Interest/Enjoyment scores of feedforward (SC+H) were above the scale midpoint 4 for all the resistance awareness levels (NA, VA and FA), i.e. whether players were ‘somewhat’ intrinsically motivated according to scale labels. For NA,  $t(11) = 6.83, p < .001$ , VA,  $t(11) = 4.50, p < .001$ , and FA,  $t(11) = 5.29, p < .001$ , the scores were significantly above the midpoint. Independent-samples t-tests with Bonferroni correction were conducted to test whether the IMI Pressure/Tension scores of feedforward (SC+H) were below the scale midpoint 4 for all the resistance awareness levels. For NA,  $t(11) = -3.71, p = .002$ , VA,  $t(11) = -5.09, p < .001$ , and FA,  $t(11) = -4.08, p < .001$ , the scores were significantly below the midpoint.

#### **H6: Feedforward leads to a higher intrinsic motivation compared to competition with others (RQ3).**

A two-way repeated measures ANOVA was conducted on the effects of game mode (B, E and H) and framing (SC and NSC) for no awareness (NA) on the IMI Interest/Enjoyment scores (Figure 5-7 bottom-left). The main effect of game mode was not significant,  $F(2, 44) = 3.01, p < .06$ . The main effect of framing was significant,  $F(1, 22) = 7.80, p = .01$ , indicating that interactive feedforward led to higher intrinsic motivation than competition with others, with a ‘large’ effect size

( $\omega^2 = 0.22$ ). The interaction effect was significant,  $F(2, 44) = 4.98, p = .01$ . A dependent-samples t-test for SC+H and NSC+H showed that interest/enjoyment in SC+H was significantly greater,  $t(22) = 3.88, p < .001$  with a ‘large’ effect size (Cohen’s  $d=1.58$ ). I therefore, accept H5.

A two-way repeated measures ANOVA with Huynh-Feldt correction was conducted on the effects of game mode (B, E and H) and framing (SC and NSC) for no awareness (NA) on the IMI Pressure/Tension scores (Figure 5-7 bottom-right). The main effect of game mode was not significant,  $F(1.59, 33.07) = 0.86, p = .41$ . The main effect of framing was significant,  $F(1, 22) = 10.80, p = .003$ , indicating that interactive feedforward led to lower pressure/tension than competition with others, with a ‘large’ effect size ( $\omega^2 = 0.29$ ). This supports H5. The interaction effect was not significant,  $F(1.59, 33.07) = 1.13, p = .32$ .

## Flow

### Game mode x Resistance awareness

A two-way repeated measures ANOVA with Huynh-Feldt correction was conducted on the effects of game mode and resistance awareness for self competition (SC) on FSQ Balance of Challenges and Skills scores (Figure 5-8 top-left). The main effect of game mode,  $F(1.78, 58.54) = 4.45, p = .02$  was significant with a ‘small’ effect size ( $\omega^2 = 0.09$ ). The main effect of awareness,  $F(2, 33) = 0.05, p = .96$ , and the interaction effect,  $F(3.55, 58.54) = 0.88, p = .47$ , were not significant. A two-way repeated measures ANOVA was conducted on the effects of game mode and resistance awareness for SC on FSQ Absorption in the Task scores (Figure 5-8 top-right). The main effect of game mode,  $F(2, 66) = 1.20, p = 0.31$ , and of awareness,  $F(2, 33) = 2.96, p = .07$ , and the interaction effect,  $F(4, 66) = 1.02, p = .40$ , were not significant.

### Game mode x Framing

A two-way repeated measures ANOVA with Huynh-Feldt correction was conducted on the effects of game mode and competition framing for NA on FSQ Balance of Challenges and Skills scores (Figure 5-8 bottom-left). The main effect of game mode,  $F(1.29, 28.27) = 2.67, p = .11$  was not significant. The main effect of framing,  $F(1, 22) = 9.27, p = .006$ , was significant with a ‘large’ effect size ( $\omega^2 = 0.26$ ). The interaction effect,  $F(1.29, 28.27) = 1.69, p = .21$ , was not significant. A

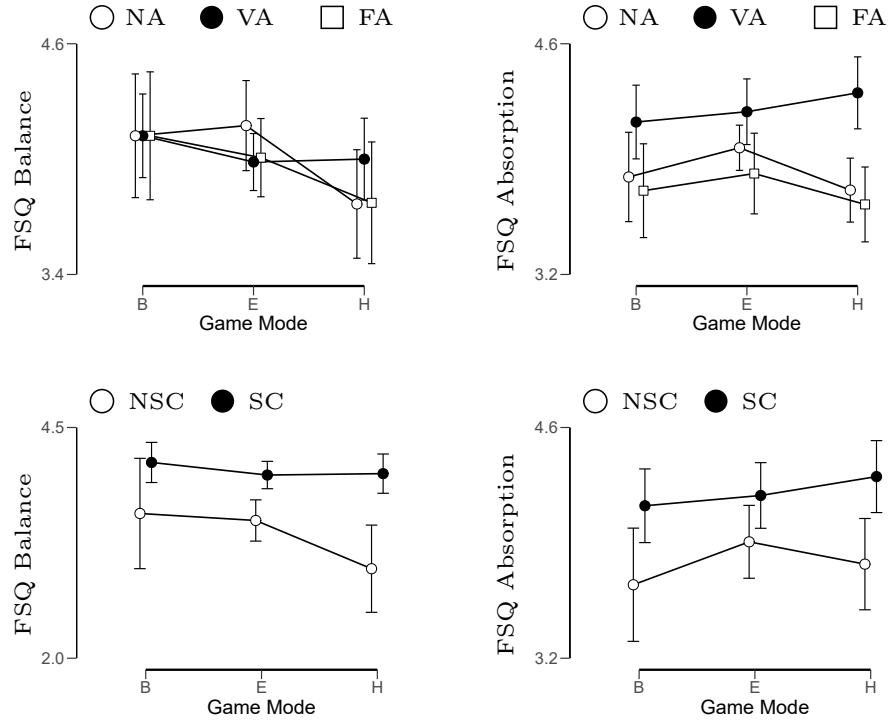


Figure 5-8: FSQ Balance of Challenges and Skills (left column) and FSQ Absorption in the Task (right column) scores for the baseline (B), equal challenge (E) and harder challenge (H) conditions for 1) self competition (SC) framing in different levels of resistance awareness (top row) and 2) without resistance awareness (NA) in self competition (SC) vs. non-self competition (NSC) framing (bottom row).

two-way repeated measures ANOVA was conducted on the effects of game mode and framing for SC on FSQ Absorption in the Task scores (Figure 5-8 bottom-right). The main effect of game mode,  $F(2, 44) = 1.25, p = .30$ , and of framing,  $F(1, 22) = 3.86, p = .06$ , and the interaction effect,  $F(2, 44) = 0.66, p = .52$ , were not significant.

### Immersion

A one-way ANOVA showed that the effect of resistance awareness (NA, VA, FA) on IEQ score was not significant,  $F(2, 33) = 1.62, p = .21$  (Figure 5-9 left). An independent-samples t-test comparing the IET scores for SC and NSC (Figure 5-

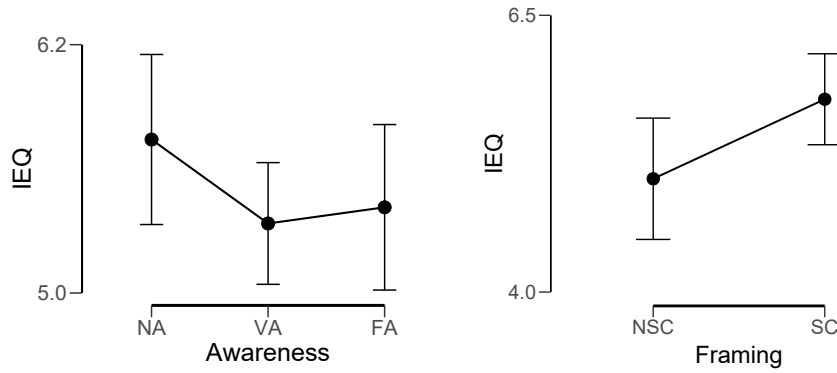


Figure 5-9: IEQ scores in different levels of resistance awareness (left) and competition framing (right).

9 right) showed that there was a significant difference between SC and NSC,  $t(22) = 2.31, p = .03$ , with a ‘large’ effect size (Cohen’s  $d=0.94$ ). That is, players felt significantly more immersed in interactive feedforward than in competition with others.

### Player Experience

Based on post-trials interviews, most players found the gameplay experience “*immersive and fun*”. Reported effects of VR were similar to those of other VR exergames [301,302]; some players felt discomfort because of VR sickness, the HMD’s heat retention and weight on the nose. My exergame focused on the lower limbs so the headset did not impede the exercise. VR sickness was mitigated by using only straight roads and lateral player movements [47,302]. While my results indicate higher intrinsic motivation when players compete against themselves (self competition) from a quantitative perspective, I was also interested in the qualitative relationship players had with the in-game avatar. Regarding players’ relationship with the in-game avatar, their comments regarding the ghost’s effect on making them perform harder corroborated my quantitative findings. With some players noting how the ghost became their primary focus. For example, one player commented, “*The ghost definitely motivated me. It gave me a reference to how well I was doing, and I wanted to beat it*”. There was contrast in the comments depending on whether players perceived the ghost as competitive (NSC) or as a self-model (SC). In NSC most players reported feelings of stress and expressed a

preference for self competition. In SC players generally reported having a more positive gameplay experience because they felt they higher chance of winning. with some players claiming they felt they *“there was no way I was able to keep up with my ghost and so just enjoyed the lights and the visuals”*. Other players described how the ghost made them feel how *“time was flying”* and how they became *“disoriented with the task”* as they focused on competing with their ghost.

## 5.3 Experiment II: Resistance Vs Speed

The implementation of feedforward involves the usage of an enhanced self-model. The enhancement of the self-model can be achieved in a cycling exergame by:

1. Increasing the bike resistance requiring the player to exert higher effort to keep up or outrace the self-model
2. Programmatically increasing the speed of the self-model

The aim of this experiment is to compare the two different kinds of enhancements to find out which kind of enhancement is more effective in improving performance and/or maintaining motivation. Increasing the speed of the self-model will make the self-model appear farther away when compared to increasing the bike resistance. Increasing the bike resistance will require greater effort from the player to achieve a certain speed. Due to the differences in the conditions, I believe that it could impact the performance improvement and intrinsic motivation. I investigated the following research question:

RQ4 How does enhancing the self-model by increasing the bike resistance differ from programmatically increasing the speed of the self-model in terms of performance improvement and intrinsic motivation?

### 5.3.1 Experimental and Exergame Design

The exergame design is similar to the previous experiment. I investigated the effectiveness of the enhancements using a counterbalanced within participants design. Three conditions Baseline (B), Resistance (R), and Speed (S) form the levels of the independent variable *game mode*. Players started with B to create a

self-model moving at the pace of their performance and in R players were asked to compete with their self-model after increasing the resistance by 10%. In the S condition the self-model is sped up in the exergame by 10% via the Unity application. I conducted the B condition first to record the speed of the enhanced models and the conditions R and S were counterbalanced.

### 5.3.2 Procedure

The players were informed about the exergame and asked to complete a demographics questionnaire. Demographics questionnaire included questions about age, gender, blood pressure, body height, weight, body composition, and number of exercise hours. They were given a choice of male/female/other for gender. They were not aware about the difference in enhancement of the enhanced self-model between the R and S conditions. A message was displayed at the beginning of every game mode condition stating “The exergame may change the intensity of the workout to make it easier or harder”. After initialising sprint resistance based on body mass, players went through a familiarisation phase which allowed them to experience the VR exergame. They were instructed to work “very hard” during the sprints and to maintain 65-70 RPM during the low intensity phases for all the phases. After players recorded their baselines, they performed the R and S conditions. At the end of each of the conditions B, R and S, players completed the IMI and left qualitative feedback about their experience. Players had a break of approx. 10 minutes between the gameplay rounds to avoid fatigue. They were allowed to take longer breaks if they were tired. At the end of the experiment players were asked to comment on their experience during the different conditions. Each session took approx. 120 minutes. I recruited 12 players (8 males, 4 females; age 22-28, mean 24) through mailing lists and posters. They were a mixture of students and employees of the University of Bath. All players gave written, informed consent and were remunerated for their time.

### 5.3.3 Outcome Variables

I used similar variables and questionnaires as Experiment I. As a measure of performance, I recorded the average power output (Power) in Watts over both sprint phases in each condition, as measured by the exercycle sensors, Power(B),



Game Mode (Within-participant)	n	Demographics	Variables	Measurement
Baseline (B)	12	M=8, F=4 Age=24±2	Power	284.31±88.10
			$\Delta$ Power	
			IMI Enjoy	5.85±0.76
			Balance	4.08 ±0.71
			Absorption	3.90±0.46
Resistance (R)			Power	328.87±97.69
			$\Delta$ Power	44.56±20.77
			IMI Enjoy	5.92 ±0.62
			Balance	3.91±0.93
			Absorption	4.13±0.55
Speed (S)			Power	309.68±95.62
			$\Delta$ Power	25.36±12.27
			IMI Enjoy	5.94 ±5.60
			Balance	3.96±0.82
			Absorption	4.19±0.53

Table 5.3: Summary of demographics and results for Experiment-II (mean  $\pm$  std. dev.).

Power(R) and Power(S). To compensate for differences in physical fitness between players, I considered each participant’s performance in the R and S game mode against their baseline B, i.e.  $\text{Power}_{R-B}$  and  $\text{Power}_{S-B}$ , which I refer to as  $\Delta$ Power in the context of game mode R or S.

To measure intrinsic motivation, I used the Intrinsic Motivation Inventory (IMI) scale [288], which has been used and validated for sports and exercise [70, 225]. The IMI comprises seven subscales, but for this experiment, I have considered Interest/Enjoyment subscale. This measures intrinsic motivation which I refer to as IMI Enjoy. In addition to that I have also considered the IMI Effort, IMI Pressure, and IMI Value which refer to the effort, felt pressure and tension, value/usefulness subscales respectively. To measure flow, I used the Flow State Questionnaire of the Positive Psychology Lab (FSQ) [216], which has been validated with exergames. It has two subscales: Balance of Challenges and Skills, and Absorption in the Task which I refer to as Balance and Absorption respectively. I hypothesise:

H6 Resistance(R) is different from Speed(S) in improving performance as mea-

sured by  $\Delta Power$  (RQ4).

H7 Resistance(R) is different from Speed(S) in improving intrinsic motivation as measured by IMI Enjoy (RQ4).

### 5.3.4 Results

A summary of the results is shown in Table 5.3. The assumptions of analysis of variance (ANOVA) were met, so I analysed the data with repeated-measures ANOVAs using the  $\omega^2$  measure for effect sizes [263], and two-tailed t-tests with Holm correction for pairwise comparisons. In cases where Mauchly's test indicated a violation of sphericity for a repeated measures ANOVA, Huynh-Feldt correction was used. According to power analyses, the ANOVAs were able to detect medium-sized effects (Cohen's  $f=0.286$ ) and the t-tests were able to detect large effects (Cohen's  $d=0.701$ ) at  $\alpha = 0.05$  with a power of 0.8. They allow us to better understand the uncertainty in the test results. The level of significance used for all tests was  $\alpha = .05$ . Plots show 95% confidence intervals of the means.

#### Power

A repeated-measures ANOVA was conducted on Game Mode (B, R and S) for *Power*. The effect of game mode on *Power* was significant ( $F(2, 22) = 37.250, p < .001^{***}$ ) with a 'small' effect size ( $\omega^2 = 0.035$ ) (Figure 5-10 top left). Post hoc comparisons using the Holm correction indicated the following. *Power(R)* is significantly different than *Power(S)* ( $t(11) = 3.396, p = .006^{**}$ ) with a large effect size (Cohen's  $d= 0.980$ ). *Power(S)* is significantly different than *Power(B)* ( $t(11) = 7.160, p < .001^{***}$ ) with a large effect size (Cohen's  $d= 2.067$ ). *Power(R)* is significantly different than *Power(B)* ( $t(11) = 7.431, p < .001^{***}$ ) with a large effect size (Cohen's  $d= 2.145$ ).

#### $\Delta Power$

A repeated-measures ANOVA was conducted on Game Mode (R and S) for  $\Delta Power$ . The effect of game mode on  $\Delta Power$  was significant ( $F(1, 11) = 11.532, p = .006^{**}$ ) with a 'small' effect size ( $\omega^2 = 0.22$ ) (Figure 5-10 top right). Post hoc comparisons using the Holm correction indicated the following.  $\Delta Power(R)$  is significantly

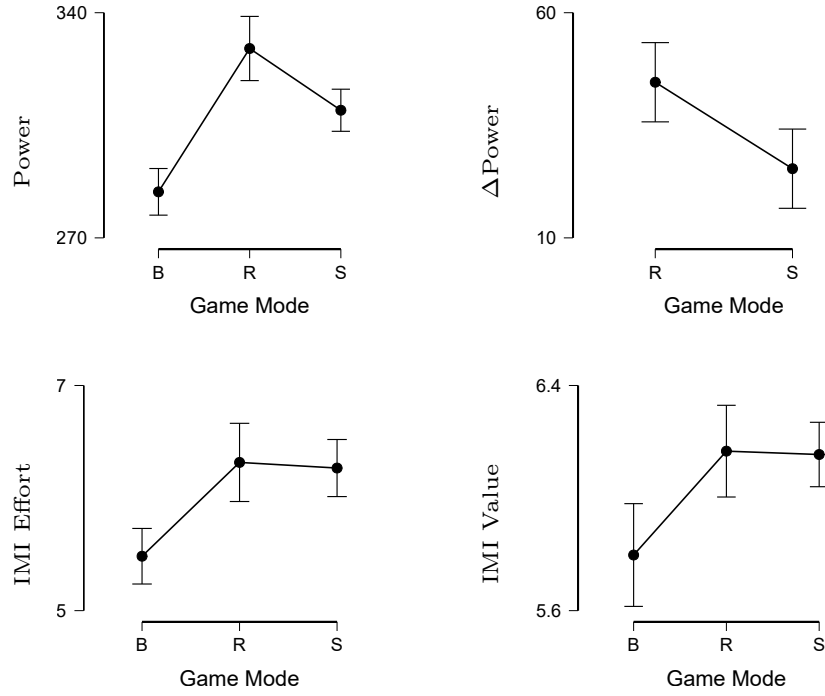


Figure 5-10: Power (left column) and  $\Delta$ Power (right column) scores for the baseline (B), resistance (R) and speed (S) conditions (top row) and IMI Effort (left column) and IMI Value (right column) scores for the baseline (B), resistance (R) and speed (S)(bottom row).

different than  $\Delta Power(S)$  ( $t(11) = 3.396, p = .006^{**}$ ) with a large effect size (Cohen's  $d = 0.980$ ). I therefore, accept H6.

### IMI Enjoy

A repeated-measures ANOVA was conducted on *Game Mode* (B, R and S) for *IMI Enjoy*. The effect of game mode on *IMI Enjoy* was not significant ( $F(2, 22) = 0.278, p = .760$ ) with no effect size ( $\omega^2 = 0.0$ ). I therefore, reject H7.

### IMI Effort

A repeated-measures ANOVA was conducted on *Game Mode* (B, R and S) for *IMI Effort*. The effect of game mode on *IMI Effort* was significant ( $F(2, 22) =$

12.916,  $p < .001^{***}$ ) with a ‘small’ effect size ( $\omega^2 = 0.221$ ) (Figure 5-10 bottom left). Post hoc comparisons using the Holm correction indicated the following. The *IMI Effort* in the R condition is not significantly different than the *IMI Effort* in the S condition ( $t(11) = 0.243, p = .813$ ) with a medium effect size (Cohen’s  $d = 0.070$ ). The *IMI Effort* in the S condition is significantly different than the *IMI Effort* in the B condition ( $t(11) = 5.863, p < .001^{***}$ ) with a large effect size (Cohen’s  $d = 1.692$ ). The *IMI Effort* in the R condition is significantly different than the *IMI Effort* in the B condition ( $t(11) = 4.110, p = .003^{**}$ ) with a large effect size (Cohen’s  $d = 1.186$ ).

### **IMI Pressure**

A repeated-measures ANOVA with Huynh-Feldt correction was conducted on Game Mode (B, R and S) for *IMI Pressure* and the effect of Competitor was not significant ( $F(0.649, 18.631) = 0.383, p = .616$ ) with no effect size ( $\omega^2 = 0.0$ ).

### **IMI Value**

A repeated-measures ANOVA was conducted on Game Mode (B, R and S) for *IMI Value*. The effect of game mode on *IMI Value* was significant ( $F(2, 22) = 8.760, p = .002^{**}$ ) with a ‘small’ effect size ( $\omega^2 = 0.041$ ) (Figure 5-10 bottom right). Post hoc comparisons using the Holm correction indicated the following. The *IMI Value* in the R condition is not significantly different than the *IMI Value* in the S condition ( $t(11) = 0.150, p = .884$ ) with a small effect size (Cohen’s  $d = 0.043$ ). The *IMI Value* in the S condition is significantly different than the *IMI Value* in the B condition ( $t(11) = 3.739, p = .010^{**}$ ) with a large effect size (Cohen’s  $d = 1.079$ ). The *IMI Value* in the R condition is significantly different than the *IMI Value* in the B condition ( $t(11) = 3.046, p = .022^*$ ) with a large effect size (Cohen’s  $d = 0.879$ ).

### **Flow Balance**

A repeated-measures ANOVA was conducted on Game Mode (B, R and S) for *Balance* and the effect of Competitor was not significant ( $F(2, 22) = 1.055, p = .365$ ) with no effect size ( $\omega^2 = 0.0$ ).

## Flow Absorption

A repeated-measures ANOVA with Huynh-Feldt correction was conducted on Game Mode (B, R and S) for *Absorption*. The effect of game mode on *Absorption* was significant ( $F(1.447, 15.915) = 4.718, p = .034^*$ ) with a ‘small’ effect size ( $\omega^2 = 0.045$ ). Post hoc comparisons with Holm correction indicated the following. The *Absorption* in the R condition is not significantly different than the *Absorption* in the S condition ( $t(11) = 1.149, p = .275$ ) with a small effect size (Cohen’s  $d = 0.332$ ). The *Absorption* in the S condition is not significantly different than the *Absorption* in the B condition ( $t(11) = 2.572, p = .078$ ) with a medium effect size (Cohen’s  $d = 0.742$ ). The *Absorption* in the R condition is not significantly different than the *Absorption* in the B condition ( $t(11) = 1.925, p = .161$ ) with a medium effect size (Cohen’s  $d = 0.556$ ).

## 5.4 Discussion

My aim was to improve the performance of players while maintaining intrinsic motivation in a VR exergame so that more people could reap the benefits of HIIT. The results showed a meaningful improvement of performance with interactive feedforward compared to competition against an unimproved self-model (SC+E) (H1), with only a marginal reduction in intrinsic motivation, i.e. within a non-inferiority margin for IMI Interest/Enjoyment of  $d_{Enjoy} = -0.3$  (H4). The performance results are in line with self-modelling theory [98] and results about the relative efficacy of video self-modelling showing current (SC+E) vs. improved behaviours (SC+H) [71]. I found a performance improvement between a baseline without competitor SC+B vs. SC+E, while other studies did not detect any performance differences between similar conditions [300, 353]. This suggests that interactive feedforward could lead to a meaningful performance improvement over an exergame without competition. At the same time, the results suggest that interactive feedforward would not be inferior with regard to intrinsic motivation compared to an exergame without competition (SC+B).

Interactive feedforward led to performance improvement in all resistance awareness conditions (NA, VA, FA) (H2). This is consistent with experiences from video self-modelling where participants are usually aware of the method and the fact

that the self-model appears improved compared to their current performance [71, 98, 100, 101, 123, 310, 311, 331, 342]. My results on the effect of resistance awareness indicate that interactive feedforward may not rely on deception but there could be meaningful effects that my study had insufficient power to detect. Interactive feedforward may have worked even better if players had been more involved and aware of the method [98, 100, 101] rather than merely being aware of increased resistance.

Interactive feedforward (SC+H) was clearly superior compared to competition with others (NSC+H), in terms of improving performance (H3), intrinsic motivation (H5), flow (balance of challenges and skills) and immersion. The results corroborated the detrimental effect competition against others can have on intrinsic motivation [89, 276, 300]. According to feedforward theory [98] and empirical evidence [310], self-models are more powerful than models of others as participants are able to identify and relate more closely to them. This is supported by frequent participant comments about relatedness (“My previous level is relevant to my condition.”) and self-efficacy (“Racing myself means there is at least a good chance that I will win!”). The increase in flow and immersion may be explained by their relation to intrinsic motivation [82, 110, 174, 182]. Players were aware that they were competing with a self-model in the SC condition and they were under the impression that they were competing with a virtual competitor in the NSC condition. This was explained in the instruction sheet they were given prior to the start of the experiment. Studies show that competition against others can have a detrimental effect on intrinsic motivation especially in less fit individuals [89, 276]. This could possibly explain why the baselines for NSC and SC so different for intrinsic motivation and flow measures.

The results of Experiment II show that increasing the resistance is a better way to enhance the self-model as it leads to higher performance improvement. Qualitative analysis of results show that 8 out of 12 players prefer increased resistance to a faster enhanced self-model. Comments such as “I felt like I had a better chance of winning” reflect that players perceived the challenge of outracing an enhanced self-model under an increased resistance more achievable than outracing a faster enhanced self-model.

### 5.4.1 Limitations

Confirming the efficacy of interactive feedforward more generally requires larger and longer studies with more than a single session. Here I explored only a single exergame with specific parameters. Future work could widen this exploration and address the lack of a comparison with traditional exercise. My players were mainly in their 20s and 30s and mostly male, which may limit the generalisability of the results. Lack of sufficient exercise is a severe problem for these age groups [352] and they are typically familiar with video games [121], so they would be a suitable target group for my proposed method. There are gender differences related to physical performance [224], exercise motivations [107], gamification [198] and competitive behaviour [253] which may have influenced my results.

I took repeated measures in a single experimental session, therefore, my results may have been influenced by familiarisation and fatigue. I used a familiarisation phase to mitigate the former and breaks to mitigate the latter. Players were allowed to take longer breaks if they were feeling tired. My comparisons focused on conditions E and H, which were counterbalanced and showed no significant order effects. My observations indicate that many players were affected by fatigue near the end of the experiment. It can be argued that since B always came before E and H, it was less affected by fatigue, which may have reduced the differences in performance between B vs. E and H. Changes in game mode and framing showed fairly large effect sizes, which suggests sufficient test power. However, my study may have been underpowered for detecting effects of resistance awareness, which could be a line of future work. Increases in performance could in part be due to a Hawthorne effect. To mitigate such effects, many of the results consider contrasts between similar treatments (e.g. SC vs. NSC) as a Hawthorne would likely have affected them similarly. Players were wearing HMDs and the IEQ results indicate that they were quite immersed in the exergame, which makes it unlikely that there was a strong awareness of the experimenter. A longitudinal field study would be the best instrument to validate the effectiveness of the method in real-world conditions.

### 5.4.2 Impact and Implications for Exergame Design

My results indicate that HIIT can be gamified effectively with interactive feedforward to help players reap the benefits of this increasingly popular type of exercise. With the proliferation of VR equipment, interactive feedforward could be implemented fairly easily in many VR exergames for cycling and other VR-safe activities such as rowing or arm crank ergometers. My results indicate that even when players are aware of resistance change, interactive feedforward could still work. So even if the resistance of an exercise cannot easily be increased automatically, it could be done by the player. An alternative to increased resistance may be a purely visual change such as an accelerated ghost. There are a number of exercise machines that already have some kind of pace-setting functionality. Although I have not explored interactive feedforward outside of VR, feedforward theory suggests that it may still have a positive effect. It would be fairly straightforward to add support for interactive feedforward to such existing exercise machines.

My study highlights that competition with others in exergames can be problematic for a general population. It suggests that it can reduce both the benefits of exercise (due to lower performance) as well as desirable psychological characteristics of the game (intrinsic motivation, flow and immersion). However, many exergames include elements of competition with others. While this works well for some players my results suggest that for exergames targeted at a general population, such game mechanics may be more appropriate as optional features. My results on framing indicate that competition against others can be replaced by self competition through interactive feedforward, with potential consequences for performance, intrinsic motivation, flow and immersion.

## 5.5 Conclusion

I proposed and evaluated interactive feedforward, a novel method to rapidly improve performance in a HIIT cycling VR exergame. Interactive feedforward is based on self competition against an improved self-model of the player, such as a recording of previous gameplay. My empirical study suggests the following conclusions, which should be considered in light of the aforementioned limitations:



1. Interactive feedforward can be effective in improving players' performance while maintaining intrinsic motivation.
2. Interactive feedforward can still work if players are aware of the increased challenge, i.e. it does not rely on deception.
3. Interactive feedforward, and self competition in general, can be superior to competition against others, leading to higher performance, intrinsic motivation, flow and immersion.

Interactive feedforward holds promise as a new method in exergames, with potential applications and opportunities in promoting positive change in people's exercise behaviour. Interactive feedforward conventionally uses self-modelling. The effectiveness of feedforward with friend-modelling (i.e. co-players with a pre-existing positive social relationship) has not been investigated. The next chapter discusses the possibility of using friend-modelling to create a "social interactive feedforward" intervention.

## Part II

### Social Interactive Feedforward

## Chapter 6

# Social Psychology and Exergames

*“No road is long with good  
company”*

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*Turkish Proverb*

Social interaction plays an important role in self-determination theory which states that people are motivated to meet their intrinsic psychological needs which are autonomy, competence, and relatedness [90]. Applications that allow people to meet these three intrinsic psychological needs will result in long term intrinsic motivation [133,290,313]. In particular, relatedness refers to being connected with one’s social circle and this is facilitated by positive social interaction. Therefore, an exergame that enables positive social interaction will increase the relatedness and it should also aim to meet the needs of autonomy and competence in order to elicit intrinsic motivation which in turn could lead to exercise adherence.

According to theory of social facilitation performance in simple tasks is enhanced by the presence of others [364]. The relationship between the players plays an important role as it impacts the social interactions in the game which can potentially influence the social game experience. A social exergame that enables people with a pre-existing positive relationship (such as a friend) can in turn positively influence the game experience. Interactive feedforward typically uses self-modelling because studies show that self-modelling is more effective than peer-modelling [99,219,308]. However, friend modelling has not been studied and

it could possibly be effective as it is supported by psychological theories such as self-determination theory and social facilitation. This chapter discusses the possibility of introducing a social element to interactive feedforward which uses friend-modelling.

## 6.1 Social Interaction and Self-determination Theory

Social interaction is defined as the process by which observable gestures, subtle deliberations, and the physiological processes of one individual influence those of another [336]. Studies show that people have very small social circles consisting of six to eleven close ties [68, 76]. Furthermore, most of people's communication is with their strong ties who they are emotionally closest to and 80 percent of their communications is with the same five to ten people [4].

This shows that people are largely influenced by those people who they are the closest to and social applications are particularly effective because they are built on the powerful platform of social bond [4]. When individuals receive a positive sanction from others and have met or exceeded expectations in a social encounter they are likely to experience happiness which will lead to displaying associative affect towards others and receive similar affect from others in the encounter [337]. Similarly, the converse is also true: when individuals receive a negative sanction from others and have not met or exceeded expectations in a social encounter they are likely to experience unhappiness which will lead to displaying dissociative affect towards others and receive similar affect from others in the encounter. This implies that positive social encounters are likely to result in experiencing happiness.

Social interaction plays a pivotal role in self-determination theory which is an important motivational theory that describes the extent to which individual behaviours are decided by oneself [90]. Applications that are designed based on self-determination theory are expected to lead to long-term intrinsic motivation [133, 290, 313]. The genesis of self-determined motivation comes from individuals' inherent tendency to cater to three basic psychological needs which are: autonomy,

which refers to being the perceived source of one's own behaviour, competence, which refers to effectively managing the ongoing interaction with the social environment and relatedness refers to a sense of connection and interaction with others within a community [90]. These needs are universal in nature as shown by inter-cultural studies [304]. Relatedness is defined as associating with others, to look after and provide for the needs of others and being looked after by others, to have a sense of community [36, 289, 333]. Self-determination theory is useful in understanding the predictors and activities that form the basis for exercise behaviour and motivation. For example, saliency in game play and intuitive controls increased competence and autonomy in players which could lead to higher self-determination [258, 265]. Research shows that when a game positively impacted feelings of competence and relatedness, those feelings led to greater enjoyment of the game [282]. Positive social interactions like playing an enjoyable video game with others improved relatedness [319] which in turn improves self-determination.

## 6.2 Social Facilitation Vs Social Loafing

Theory of social facilitation states that behaviour in simple tasks is improved by the mere presence of others [364]. Zajonc classified research in the area of social facilitation in terms of two experimental paradigms: audience effects and co-action effects. The audience effects paradigm involves the observation of behaviour when it occurs in the presence of passive spectators. Early studies showed that people performed better when they were under observation when doing simple motor tasks [40, 332]. The co-action effects paradigm tests behaviour when one performs an action in the presence of other people who are also doing the same activity and studies show that presence of others as co-actors increases the dominant response (i.e. the response that they are familiar with and has the greatest habit strength).

Interestingly, a vast literature review shows that arousal also result in an increase of dominant responses [309]. Improvement in performance is noted due to social facilitation because presence of others enhances competitiveness [334] and increases an individual's internal drive [364]. A study by Worringham et al. shows that a group of runners which encountered a female facing the runner at the halfway

point showed a significant acceleration when compared to the group that ran alone and the group that encountered a female seated with her back to the runner [359].

Social loafing refers to the tendency of individuals to expend less effort when working together than when working by themselves. This detrimental effect of social loafing has been noticed in group tasks that require collective pooling of individual members' inputs and not in tasks that involve coaction in which an individual's effort is indispensable to the outcome of the task [192]. This has been explained by a "minimizing strategy where players were motivated to work as hard as necessary to gain credit for good performance or to avoid blame for a bad one. Whenever the experimenter was unable to monitor individual outputs directly, performers sloughed off" [156]. Another study shows that both social facilitation and loafing are complementary and results consistently showed that evaluation and coaction lead to better performance [155]. Therefore, to avoid social loafing and enhance social facilitation a task should involve coaction and should be evaluable. The effect of virtual social facilitation was explored by using a VR stationary bike and introducing competitive avatars and the results showed that it increased exercise effort among more competitive exercisers [9]. Notable differences between the study I am proposing and this study by Anderson et al. is that I am investigating the effectiveness of social interactive feedforward in high intensity exercising which involves enhanced interactive models.

### **6.3 Conditioning, Social Learning Theory, and Social Cognitive Theory**

Classical conditioning is also referred to as Pavlovian or respondent conditioning. Classical conditioning was discovered by Pavlov refers to modification of behaviour through association of stimuli. When an unconditioned stimulus is paired with an originally neutral conditioned stimulus and an organism is repeatedly exposed to the pairing, the organism reacts to the conditioned stimulus the same way as the unconditioned stimulus as a result of conditioned association [361].

Operant conditioning is also a type of association learning. It is based on Thorndike's law of effect which states that behaviour that is followed by re-

warding outcomes tend to be recurrent and behaviour followed by punishing outcomes does not tend to recur [327–329]. Skinner amended the law to reinforcement: behaviour that is reinforced is likely to be strengthened and behaviour that is not reinforced tends to be weakened [115]. These conditioning models can possibly be relevant to exergaming. The behaviour of exercising may be reinforced by the pleasant experience of playing an exergame.

Social learning theory explains the process of behaviour imitation by observing others. Social learning theory, put forth by Albert Bandura, is built on classical conditioning and operant conditioning. Behaviour imitation acquired through observational learning of others in the environment is mediated by the following processes: attention, retention, reproduction and motivation [21]. Attention refers to the degree to which one's attention is captured by a certain behaviour. Retention refers to how memorable a certain behaviour is considered to be. Reproduction refers to the physical capability of an individual to imitate the observed behaviour. Motivation refers to the will to imitate the observed behaviour which depends on if the individual perceives the behaviour to be more rewarding than punishing.

The social learning theory aptly fits into social exergaming. Each of the mediating processes can potentially be enhanced by using an enjoyable exergame. Observational learning can be made possible by placing models of others exercising in the virtual exergame environment. Attention of the player can be captured by allowing them to play an immersive VR exergame and it can be made memorable by using an engaging gameplay. It can be made reproducible by optimally challenging the player and it can be made motivating by making the experience of exercising rewarding by using gamification rather than punishing due to muscular pain and fatigue.

Bandura extended the social learning theory to form social cognitive theory. The theory posits that when an individual observes modelled behaviour and its outcomes, one emulates it by recalling the series of steps and uses it to direct future behaviour. This theory follows the triadic reciprocal causation consisting of 3 determinants: personal, behavioural, and environmental [24]. The personal factor refers to one's self-efficacy towards that behaviour. The behavioural factor refers to the feedback of the behaviour. The environmental factor refers to the

impact of the surrounding on the person's capability to imitate the behaviour. The determinants of the extended social cognitive theory can also be positively influenced by using an engaging exergame. A study by Krause et al. shows that successful exergaming implementation can enhance self-efficacy [201] which improves the personal determinant of social learning theory. Both behavioural and environmental determinants can be provided by giving instantaneous feedback of the exercise via the exergame and positively influenced by an engaging gameplay respectively.

## 6.4 Social Comparison Theory, Exercise Partners, and Competition

Social comparison proposed by Festinger [116] is comparing oneself with others for self-evaluation, self-improvement and self-enhancement [320,358]. The most important variables that affect social comparison are: the expertise of the person one is comparing herself to, similarity with that person, and previous agreement with that person [315]. Studies show that in conditions in which self-evaluation and self-improvement play an important role, individuals prefer to compare themselves with someone who is slightly better-off i.e. an upward comparison [144,348,349,355]. Furthermore, if the comparison dimension is a skill acquired through practice or one that increases naturally with maturity, upward comparisons are considered to be uplifting because it informs the individual that such achievements are within reach, and one feels good progressing toward the target's superior state [58].

People make upward comparisons in hopes of enhancing their self-assessments and state that it serves indirectly through self-improvement and sometimes directly by enhancing the self [77]. Self-evaluations based on comparisons with others become stronger when they compare themselves with people who are similar to them [116] specifically with regard to the dimension being evaluated [358]. Therefore, upward comparisons with people who are similar to themselves in the dimension being evaluated leads to an uplifting self-assessment potentially leading to improvement.

Studies show that exercising with friends or peers increases exercise adherence [112,207]. Participants exercised harder when the perceived fitness level of an



exercise partner was high than when it was low [273] and another study shows that exercising with a fitter exercise partner boosts a high intensity exercise session [87]. Physical activity levels among members of one activity tracking social networking site was positively associated with the physical activity levels of their connections [63]. Competition enhances exercise performance as it leads to higher levels of arousal [324]. Head to head competition encourages participants to increase their performance predominantly due to an increased anaerobic energy yield [78].

## 6.5 Social Games

According to the literature review done by Baumeister et al., the desire for interpersonal attachments is a powerful, fundamental, and pervasive motivation. They further state that people form social attachments easily and preserve existing bonds [36]. This overwhelming need to belong fuels social networking. Social networking sites such as Facebook and Instagram are extremely popular with over billions of users. Their powerful influence stems from the fact that they built around people and their relationships.

According to Benkler, people are motivated to use social media for the following reasons: social connectedness, psychological well-being, gratification, and material gain [39]. Although technology develops at a rapid pace, human behaviour patterns change very slowly as they are a product of thousands of years of evolution. Applications aiming to modify human behaviour are likely to be successful if they provide a way for people to connect and interact with their tightly knit social circle who have the most influence on them. One of the most remarkable features of social networks is its homogeneity among clusters of friends. According to Lewis et al. there are two possible explanations for homogeneity among friends. One reason could be that friends may be similar due to social selection or homophily i.e. similar people befriend one another [84,227]. The other reason is homogeneity between characteristics of friends which could be a result of peer influence or diffusion. Diffusion is propensity for behaviours to proliferate through social ties resulting in friends resembling one another over time [66,281]. Both explanations strengthen the argument that friends have a lot of common characteristics and

can potentially be very influential in behaviour modification and/or motivating people to do an activity.

Social games combine the influential social element and engaging gamification to motivate players. They have exponentially grown in the last few years with popular social games such as FarmVille and World of Warcraft amassing millions of players. According to Granic et al. more than 70% of games entail playing with a partner and even single player games usually involve a virtual partner which shows how important social interaction is in gaming [140]. Social games can be used for a variety of motivational or behaviour modification purposes.

Social gaming can motivate learners and provided an integrative theory of gamification [205]. An online social network with gamification elements was deployed and students were motivated to complete tests by offering them social rewards in the form of virtual badges. The system was highly successful with 29% of players completing gamified optional multiple choice quizzes and finding it to be enjoyable.

Social games can be particularly useful for examining customer relationship development. This is because social game products primarily utilise mechanics in game design itself that are aimed at customer relationships. Their "essential viral capabilities in acquiring new users and for using players' contacts as part of the gameplay" can also be used to promote exercising in social exergames. Furthermore, gamification combined with social element has potential to make exercising intrinsically motivating leading to increased exercise adherence.

A study by Mueller et al. shows that exergames can facilitate social play including mediated exergames and the design of the game can be a contributing factor [242]. A study by Gajadhar et al. states that the presence of a co-located co-player can significantly enhance fun, challenge, and perceived competence in the game. They report that social context is an integral factor of player enjoyment and should be integrated in the game [128].

Another study by Mueller et al. investigated the effects of virtual co-presence of co-players they have a social relationship with. They designed a system in which spatialised audio based on heart rate would allow players to *virtually* run

together [241]. They recruited 17 players who were paired with their friends or siblings. They concluded that social support enhances engagement with the physical activity based on a qualitative analysis of players' experience. Players reported that the system enabled them to feel co-located even though they were not together physically. They reported that in some cases it was even better than jogging together because the system enabled them to feel co-located even if their physical capabilities were different so one player didn't have to wait for the other. They also reported that social presence which refers to the sense of being with another person enhanced enjoyment.

A literature review by Kooiman et al. says that self-determination requires social nourishment. Social nourishment refers to the tendency of a social event to impart positive or negative propensities in one's reaction to stimuli [199]. They also state that when learners in touch with other people can influence the overall well-being of the learner. According to a commentary by Teixeira et al. self-determination model is person-centred and being surrounded by a "positive emotional climate" i.e. in the company of people who have "genuine empathy and unconditional regard" about the learner's successful progress plays a crucial role in the success of behaviour change leading to enhanced integration, growth and wellness [322, 341]. Applying their comment in my context implies that if a player trains with friends who are likely to be genuinely concerned about their well being it will potentially pave way for exercise adherence.

A study by Balnaves et al. discussed the social value of the widely played social game, Farmville [20]. The game had gathered 85 million users at its peak [102]. Farmville is a farming-simulator game which allows players to virtually manage a farmland by growing crops and animals. According to the essay by Liszkiewicz, players play Farmville despite its lacklustre aesthetics and repetitive gameplay primarily because of the social element [210]. The game fosters social interaction and allows players to feel a sense of community without having to be physically present with other players [20]. This further corroborates the importance of virtual co-presence of co-players in the gameplay.

## 6.6 Social Exergames

Social exergames bring together the enjoyable elements of gamification and social bonding to alleviate the unpleasant effects of exercising such as fatigue and muscular pain making it an enjoyable experience. According to a six-week study by Kaos et al. people who engage in social play have an enhanced exergame adherence compared to those in individual play [189]. The superior adherence found in social play was attributed to enabling players to feel a sense of belonging which is a crucial and universal human need [36].

Chan et al. identified self-determination theory, gamification, competition and cooperation, situational interest, and social interaction as components that play an integral role in promoting adherence. Their results show that the social aspect of the exergame in particular motivates players resulting in continued exergame play. They found that social support and communication are key mediators for encouraging behaviour change. They also found that effective player matchmaking strategies for increasing social connectedness is an important area of future research [67].

Bekker et al. created interactive play objects that can simulate social interactions and exercise [37]. The gameplay was influenced by behaviour theories such as the self-efficacy theory. Positive player experiences as a result of the game and motivating feedback increase self- efficacy which in turn leads to increased adherence. Their finding states that social interaction can be evoked using a game played by multiple players and the kind of association between the players can impact the kind of social interactions that take place. This implies that the kind of relationship between the players is very important because it affects the social interactions in the game which can potentially influence the social game experience. Therefore, in my social exergame, I use pairs of friends so that the pre-existing positive relationship can in turn positively influence the game experience.

## 6.7 Mirror Neurons and Interactive Feedforward

Mirror neurons, neural circuits responsible for modelled behaviour, get activated when one performs a task or observes the task being performed by others [166].

Dowrick explains that feedforward triggers the firing of mirror neurons as a result of behaviour imitation [99]. The psychophysiological training technique, feedforward uses an enhanced self-model because several studies show that self-modelling is superior to peer modelling [99, 219, 308]. However, previous studies have not explored using an enhanced "friend's" model in the context of the feedforward method.

Greater mirror neuron response was observed during video modelling by self or a family member than by an unfamiliar person [260]. It is possible that the feedforward method can extend to using a friend as an enhanced model. This is because friends share a close personal relationship and mirror neurons are fired at a higher intensity when people are familiar with the enhanced model thus identifying with it. This could suggest that adding the social component to interactive feedforward could increase exercise adherence.

## 6.8 Summary

This chapter reviews various social psychology theories and discusses the important role of positive social interaction in potentially enabling continued exercise adherence. In particular, exergames that enable interaction with people that they have a pre-existing positive social relationships such as a friend could improve player experience [37]. Although interactive feedforward typically uses self-modelling, the vast literature showing the effectiveness of facilitating a positive social interaction with friends justifies investigating friend-modelled interactive feedforward. The next chapter introduces a social element to interactive feedforward in the form of friend modelling and presents an empirical study comparing friend modelled interactive feedforward i.e. social interactive feedforward with self-modelled interactive feedforward.

# Chapter 7

## Social Interactive Feedforward in High Intensity VR Exergaming

*“A champion needs a motivation  
above and beyond winning.”*

---

*Pat Riley*

### 7.1 Introduction

Several studies show that feedforward leads to rapid improvement in performance and enjoyment in a short span of time [71, 98, 100, 101, 123, 310, 311, 331, 342]. Conventional feedforward uses self-modelling because studies showed that self-modelling is more effective than peer or stranger modelling [99, 219, 308]. This reasoning is supported by neural activities such as mental time travel, prospection (envisioning possible futures) and mirror neurons. However, a closer look at the previous research suggests that the use of feedforward between people who they have an intimate interpersonal relationship with has not been investigated. Neural activities which underpin the use of self-modelling in feedforward can be extended to accommodate friend modelling.

Buckner et al.’s suggestion that prospection enables envisioning the future and conceiving the viewpoint of others implies that prospection could be extended to

projecting the future from the viewpoint of their friends [57]. Similarly, greater mirror neuron response was observed during video modelling by self or a family member than by an unfamiliar person [260] and therefore, it is safe to say that mirror neurons are more likely to be activated when using models of people the individual shares a close bond with such as friends. This warrants the examination of feedforward in a social context using friend modelling. Other well established theories such as self-determination theory, social facilitation, social cognitive theory, and social comparison theory also justify the inclusion of a social element in feedforward and therefore, I investigate the effectiveness of social interactive feedforward in this chapter. I define social interactive feedforward as using an enhanced model of a friend showing previously unachieved performance levels that players relate, compete, and interact with at real-time in a VR feedforward experience resulting in an expeditious improvement in performance while having a pleasant user experience.

The aim of this experiment is to introduce a social element to interactive feedforward for VR exergaming by introducing an enhanced virtual model of a friend of the player as a competitor. I pair people who have roughly the same power output and I increase the resistance by 10% in both social interactive feedforward and self-modelled feedforward. Social comparison theory can be useful in encouraging an active life-style because studies show that people were prone to mimicking the behaviour of their peers [116, 213] and are likely to exercise when observing others around them also exercising [213].

In summary, I investigated the following research questions:

**RQ1** How effective is social interactive feedforward in improving performance as measured by average power output when compared to conventional interactive feedforward?

**RQ2** How effective is social interactive feedforward in improving intrinsic motivation when compared to conventional interactive feedforward?

## 7.2 Experiment III: Social Interactive Feedforward

### 7.2.1 Exergame and Experimental Design

I used the same exergame design as the one used in Experiments I and II. I used a low volume high intensity interval training protocol with 60 seconds warm-up, 30 seconds sprint, 90 seconds recovery, 30 seconds sprint, and 90 seconds cool-down. I investigated the effectiveness of using an enhanced friend's model in interactive feedforward using a counterbalanced within participants design.

Three conditions Friend, Self, and Stranger form the levels of the independent variable Competitor after recording the baseline. Friends arrived together and one had to wait while the other player recorded their baseline model. This thesis' first experiment involved one group that competed with themselves and the other group was led to believe that they were competing with a virtual competitor. The design decision of displaying "This is you" for the self-competition group was sufficient to inform the players in addition to giving an instruction sheet to both the groups clearly instructing them about whom they are competing with. This experiment involves three different levels and players competed with enhanced models of themselves, their friend, and a stranger which moved at the pace of their friend. To make sure players constantly associated the enhanced models to their Friend, Self, or Stranger conditions, I took photos of them to be attached to the models.

During the baseline, I recorded the players' performance and their friends' to create the enhanced models. In the Friend condition, I attempted to elicit a feedforward effect by, in addition to competing with the friend's model, increasing the resistance by 10%. The friend's model had a picture of their friend attached to the back to help the players associate the model to their friends.

In the Self condition, I attempted to elicit a feedforward effect by, in addition to competing with the self-model, increasing the resistance by 10%. The self-model had a picture of the players attached to the back to help the players associate the model to themselves. The Stranger condition is the control condition and players were competing with a model which moved at the same speed as the friend's model under an increased resistance by 10% but had a picture of a stranger attached to



Game Mode (within-participants)	n	Demographics	Variables	Measurement
Stranger(S)	20	M=15, F=5 Age=22.5±3.29	Power	370.79±88.68
			$\Delta$ Power	33.71±34.80
			IMI Enjoy	5.35±0.91
			Balance	3.95±0.88
			Absorption	3.85±0.71
Self (S)			Power	377.05±96.06
			$\Delta$ Power	39.98±36.93
			IMI Enjoy	5.58±0.79
			Balance	4.16±0.68
			Absorption	3.99±0.75
Friend (S)			Power	394.88±96.57
			$\Delta$ Power	57.81±34.00
			IMI Enjoy	5.94±0.60
			Balance	4.17±0.65
			Absorption	4.29±0.57

Table 7.1: Summary of demographics and results for Experiment-III (mean  $\pm$  std. dev.).

it to help the players associate the model to a stranger.

The players were not aware that the enhanced models in the Stranger condition and the Friend condition move in the same pace. Players were informed that they were competing with: a friend's model in the Friend condition, self-model in the Self condition and a stranger's model in the Stranger condition. A message was displayed at the beginning of Friend, Self and Stranger conditions stating "The exergame may change the intensity of the workout to make it easier or harder". I conducted the Baseline condition first to record the speed of the enhanced models and the conditions Friend, Self, and Stranger were counterbalanced.

### **Outcome Variables**

I used similar outcome variables to Experiment I and II. As a measure of performance, I recorded the average power output (Power) in Watts over both sprint phases in each condition as measured by the exercycle sensors. To compensate for differences in physical fitness between players, I considered each player's performance in the Self, Friend, and Stranger game mode against their baseline, i.e. Power (Self-Baseline), Power (Friend-Baseline), and Power (Stranger-Baseline) which I refer to as  $\Delta$ Power in the context of game mode Self, Friend, and Stranger respectively. I used the IMI Enjoyment scale, IMI Enj to measure intrinsic motivation. To measure flow, I used the Flow State Questionnaire's subscales: Balance of Challenges and Skills which I refer to as Balance and Absorption in the Task which I refer to as Absorption.

### **Hypotheses**

Based on related work, I had the following hypotheses:

- H1** The Friend condition improves performance more than the Self condition and the Stranger condition.
- H2** The Friend condition improves intrinsic motivation more than the Self condition and the Stranger condition.

### 7.2.2 Procedure

Players were told that it was a social exergaming experiment and they were asked to partner with friends who were more or less as fit as they were. The players were informed about the experimental conditions and asked to complete a demographics questionnaire. Demographics questionnaire included questions about age, gender, blood pressure, body height, weight, body composition, and number of exercise hours. They were given a choice of male/female/other for gender. The players were told that the purpose of the baseline condition was to record their performance and their friend's performance for the models.

They were not aware that the Stranger's enhanced model moves at the same pace as the enhanced model in the Friend's condition. A message was displayed at the beginning of every game mode condition stating "The exergame may change the intensity of the workout to make it easier or harder". The average of the baseline difference in number of revolutions between the player pairs including the one mixed gender pair was  $M=0.77(SD=14.86)$ . Players also recorded their answer on a self-reported friendship question which was a 7 point Likert scale proposed by Hays et al. [158]. The average score was  $M=4.05(SD=0.83)$ .

After initialising sprint resistance based on body mass, players went through a familiarisation phase which allowed them to experience the VR exergame. They were instructed to work "very hard" during the sprints and to maintain 65-70 RPM during the low intensity phases for all the phases. After players recorded their baselines, they performed the Friend, Self and Stranger conditions in a counterbalanced order. Players performed all the other conditions in private without the physical presence of their friend to influence them. At the end of each of the conditions Friend, Self and Stranger, players completed the IMI and left qualitative feedback about their experience. Players had a break of approximately 10 minutes between the gameplay rounds to avoid fatigue. They were allowed to take longer breaks if they were tired. At the end of the experiment players were asked to comment on their experience during the different conditions. Each session took approximately 180 minutes.

## Participants

Players were recruited through mailing lists and posters and were asked to sign up with their friends who are more or less as fit as they are. I recruited 20 players in total (15 male, 5 female, age 18-28, mean 22.5), who were students and employees of the University of Bath. I screened them with the Physical Activity Readiness Questionnaire (PAR-Q) [110] and excluded players with health risks or a resting blood pressure greater than 140/90 mmHg. All players gave written, informed consent, and were remunerated for their time.

### 7.2.3 Results

A summary of the results is shown in Table 7.1. The assumptions of analysis of variance (ANOVA) were met, so I analysed the data with repeated-measures ANOVAs using the  $\omega^2$  measure for effect sizes [263], and two-tailed t-tests with Holm correction for pairwise comparisons. According to power analyses, the ANOVAs were able to detect medium-sized effects (Cohen's  $f=0.286$ ) and the t-tests were able to detect large effects (Cohen's  $d=0.701$ ) at  $\alpha = 0.05$  with a power of 0.8. They allow us to better understand the uncertainty in the test results. Because of my within-participants design, I calculated and tested repeated measures correlations using Pearson correlations. The level of significance used for all tests was  $\alpha = .05$ . Plots show 95% confidence intervals of the means.

## Performance

A repeated-measures ANOVA was conducted on Competitor (Stranger, Self and Friend) for  $\Delta Power$ . The effect of Competitor was significant ( $F(2, 38) = 7.224, p = .002^{**}$ ) with a 'medium' effect size ( $\omega^2 = 0.067$ ) (Figure 7-1 top-left).  $\Delta Power$  in Friend was significantly higher compared to Self ( $t(19) = 2.304, p = .016^{*}$ ) with a 'medium' effect size (Cohen's  $d=0.515$ ) and also significantly higher compared to Stranger ( $t(19) = 4.265, p < .001^{***}$ ) with a 'large' effect size (Cohen's  $d=0.954$ ) so I accept H1.  $\Delta Power$  in Self was not significantly higher when compared to Stranger ( $t(19) = 1.017, p = .161$ ) with a 'small' effect size (Cohen's  $d=0.227$ ).

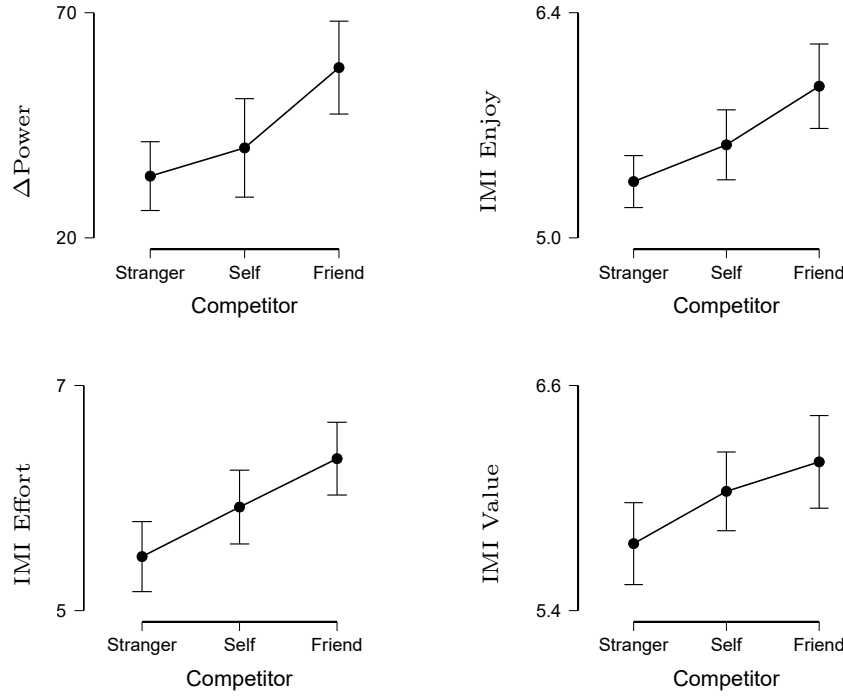


Figure 7-1:  $\Delta$ Power (left column) and IMI Enjoy (right column) scores for the Stranger, Self, and Friend conditions (top row) and IMI Effort (left column) and IMI Value (right column) scores for the Stranger, Self, and Friend conditions (bottom row).

### IMI Enjoy

A repeated-measures ANOVA was conducted on Competitor (Stranger, Self and Friend) for *IMI Enj*. The effect of Competitor was significant ( $F(2, 38) = 8.253, p = .001^{**}$ ) with a ‘medium’ effect size ( $\omega^2 = 0.081$ ) (Figure 7-1 top-right). *IMI Enj* in Friend was significantly higher compared to Self ( $t(19) = 2.055, p = .027^*$ ) with a ‘small’ effect size (Cohen’s  $d=0.460$ ) and also significantly higher compared to Stranger ( $t(19) = 4.022, p < .001^{***}$ ) with a ‘large’ effect size (Cohen’s  $d=0.899$ ) so I accept H2. *IMI Enj* in Self was significantly higher compared to Stranger ( $t(19) = 2.099, p = .025^*$ ) with a ‘small’ effect size (Cohen’s  $d=0.469$ ).

### IMI Effort

A repeated-measures ANOVA was conducted on Competitor (Stranger, Self and Friend) for *IMI Effort*. The effect of Competitor was significant ( $F(2, 38) = 8.060, p = .001^{**}$ ) with a ‘medium’ effect size ( $\omega^2 = 0.112$ ) (Figure 7-1 bottom-left). *IMI Effort* in Friend was significantly higher compared to Self ( $t(19) = 1.928, p = .034^*$ ) with a ‘small’ effect size (Cohen’s  $d=0.431$ ) and also significantly higher compared to Stranger ( $t(19) = 4.106, p < .001^{***}$ ) with a ‘large’ effect size (Cohen’s  $d=.918$ ). *IMI Effort* in Self was significantly higher compared to Stranger ( $t(19) = 2.046, p = .027^*$ ) with a ‘small’ effect size (Cohen’s  $d=0.458$ ).

### IMI Pressure

A repeated-measures ANOVA was conducted on Competitor (Stranger, Self and Friend) for *IMI Pressure* and the effect of Competitor was not significant ( $F(2, 38) = 0.139, p = .871$ ) with a no effect size ( $\omega^2 = 0.0$ ). *IMI Pressure* in Friend was not significantly higher compared to Self ( $t(19) = 0.346, p = .367$ ) with a ‘small’ effect size (Cohen’s  $d=.077$ ) and was not significantly higher compared to Stranger ( $t(19) = 0.083, p = .533$ ) with a ‘small’ effect size (Cohen’s  $d=.019$ ). *IMI Pressure* in Self was not significantly higher compared to Stranger ( $t(19) = 0.509, p = .692$ ) with a ‘small’ effect size (Cohen’s  $d=.114$ ).

### IMI Value

A repeated-measures ANOVA was conducted on Competitor (Stranger, Self and Friend) for *IMI Value*. The effect of Competitor was significant ( $F(2, 38) = 4.192, p = .023^*$ ) with a ‘small’ effect size ( $\omega^2 = 0.033$ ) (Figure 7-1 bottom-right). *IMI Value* in Friend was not significantly higher compared to Self ( $t(19) = 1.000, p = .165$ ) with a ‘small’ effect size (Cohen’s  $d=.224$ ) and was significantly higher compared to Stranger ( $t(19) = 2.683, p = .007^{**}$ ) with a ‘medium’ effect size (Cohen’s  $d=.600$ ). *IMI Value* in Self was significantly higher compared to Stranger ( $t(19) = 2.041, p = .028^*$ ) with a ‘small’ effect size (Cohen’s  $d=0.456$ ).

### Flow Balance

A repeated-measures ANOVA was conducted on Competitor (Stranger, Self and Friend) for *Balance* and the effect of Competitor was not significant ( $F(2, 38) =$

1.709,  $p = .195$ ) with a tiny effect size ( $\omega^2 = 0.007$ ). *Balance* in Friend was not significantly higher compared to Self ( $t(19) = 0.107, p = .458$ ) with a tiny effect size (Cohen's  $d=0.024$ ) and was significantly higher compared to Stranger ( $t(19) = 1.951, p = .033^*$ ) with a 'small' effect size (Cohen's  $d=0.436$ ). *Balance* in Self was not significantly higher compared to Stranger ( $t(19) = 1.329, p = .100$ ) with a 'small' effect size (Cohen's  $d=0.297$ ).

### Flow Absorption

A repeated-measures ANOVA was conducted on Competitor (Stranger, Self and Friend) for *Absorption*. The effect of Competitor was significant ( $F(2, 38) = 9.857, p < .001^{***}$ ) with a 'medium' effect size ( $\omega^2 = 0.060$ ). *Absorption* in Friend was significantly higher compared to Self ( $t(19) = 2.716, p = .007^{**}$ ) with a 'medium' effect size (Cohen's  $d=0.607$ ) and also significantly higher compared to Stranger ( $t(19) = 4.489, p < .001^{***}$ ) with a 'large' effect size (Cohen's  $d=1.004$ ). *Absorption* in Self was not significantly higher than Stranger ( $t(19) = 1.510, p = .074$ ) with a 'small' effect size (Cohen's  $d=.338$ ).

### Correlations of Sports Orientation

Players who are competition, win, and goal oriented are likely to perform well, have high intrinsic motivation and flow scores in a competitive and goal oriented race. Therefore, I tested the following correlations:

$\Delta Power(Friend)$  was significantly positively correlated with Comp SOQ ( $r = 0.632, p = .001^{**}$ ).  $\Delta Power(Self)$  was significantly positively correlated with Comp SOQ ( $r = 0.502, p = .012^*$ ).  $\Delta Power(Stranger)$  was significantly positively correlated with Comp SOQ ( $r = 0.633, p = .001^{**}$ ).  $\Delta Power(Friend)$  was significantly positively correlated with Win SOQ ( $r = 0.535, p = .008^{**}$ ).  $\Delta Power(Self)$  was significantly positively correlated with Win SOQ ( $r = 0.383, p = .048^*$ ).  $\Delta Power(Stranger)$  was significantly positively correlated with Win SOQ ( $r = 0.468, p = .019^*$ ).  $\Delta Power(Friend)$  was significantly positively correlated with Goal SOQ ( $r = 0.567, p = .005^{**}$ ).  $\Delta Power(Self)$  was significantly positively correlated with Goal SOQ ( $r = 0.559, p = .005^{**}$ ).  $\Delta Power(Stranger)$  was significantly positively correlated with Goal SOQ ( $r = 0.619, p = .002^{**}$ ).

*IMI Enj(Friend)* was significantly positively correlated with Comp SOQ ( $r = 0.413, p = .035^*$ ). *IMI Enj(Self)* was significantly positively correlated with Comp SOQ ( $r = 0.455, p = .022^*$ ). *IMI Enj(Stranger)* was significantly positively correlated with Comp SOQ ( $r = 0.441, p = .026^*$ ). *IMI Enj(Friend)* was not significantly positively correlated with Win SOQ ( $r = 0.279, p = .117$ ). *IMI Enj(Self)* was not significantly positively correlated with Win SOQ ( $r = 0.248, p = .146$ ). *IMI Enj(Stranger)* was not significantly positively correlated with Win SOQ ( $r = 0.211, p = .186$ ). *IMI Enj(Friend)* was not significantly positively correlated with Goal SOQ ( $r = 0.247, p = .147$ ). *IMI Enj(Self)* was significantly positively correlated with Goal SOQ ( $r = 0.567, p = .005^{**}$ ). *IMI Enj(Stranger)* was significantly positively correlated with Goal SOQ ( $r = 0.584, p = .003^{**}$ ).

*IMI Effort(Friend)* was not significantly positively correlated with Comp SOQ ( $r = 0.224, p = .171$ ). *IMI Effort(Self)* was not significantly positively correlated with Comp SOQ ( $r = 0.164, p = .245$ ). *IMI Effort(Stranger)* was not significantly positively correlated with Comp SOQ ( $r = 0.235, p = .159$ ). *IMI Effort(Friend)* was not significantly positively correlated with Win SOQ ( $r = 0.200, p = .199$ ). *IMI Effort(Self)* was not significantly positively correlated with Win SOQ ( $r = 0.182, p = .221$ ). *IMI Effort(Stranger)* was significantly positively correlated with Win SOQ ( $r = 0.489, p = .014^*$ ). *IMI Enj(Friend)* was not significantly positively correlated with Goal SOQ ( $r = 0.044, p = .427$ ). *IMI Enj(Self)* was not significantly positively correlated with Goal SOQ ( $r = 0.212, p = .185$ ). *IMI Enj(Stranger)* was not significantly positively correlated with Goal SOQ ( $r = 0.336, p = .074$ ).

*IMI Pressure(Friend)* was not significantly positively correlated with Comp SOQ ( $r = -0.056, p = 0.592$ ). *IMI Pressure(Self)* was not significantly positively correlated with Comp SOQ ( $r = 0.012, p = 0.481$ ). *IMI Pressure(Stranger)* was not significantly positively correlated with Comp SOQ ( $r = -0.146, p = 0.269$ ). *IMI Pressure(Friend)* was not significantly positively correlated with Win SOQ ( $r = -0.066, p = 0.609$ ). *IMI Pressure(Self)* was not significantly positively correlated with Win SOQ ( $r = -0.064, p = 0.394$ ). *IMI Pressure(Stranger)* was significantly positively correlated with Win SOQ ( $r = 0.409, p = .037^*$ ). *IMI Pressure(Friend)* was not significantly positively correlated with Goal SOQ ( $r = -0.122, p = 0.696$ ). *IMI Pressure(Self)* was not significantly correlated with



Goal SOQ ( $r = -0.096, p = 0.344$ ). *IMI Pressure(Stranger)* was not significantly positively correlated with Goal SOQ ( $r = -0.258, p = 0.136$ ).

*IMI Value(Friend)* was significantly positively correlated with Comp SOQ ( $r = 0.449, p = .024^*$ ). *IMI Value(Self)* was significantly positively correlated with Comp SOQ ( $r = 0.467, p = .019^*$ ). *IMI Value(Stranger)* was not significantly positively correlated with Comp SOQ ( $r = 0.274, p = .121$ ). *IMI Value(Friend)* was significantly positively correlated with Win SOQ ( $r = 0.568, p = .005^{**}$ ). *IMI Value(Self)* was significantly positively correlated with Win SOQ ( $r = 0.573, p = .004^{**}$ ). *IMI Value(Stranger)* was not significantly positively correlated with Win SOQ ( $r = 0.260, p = .134$ ). *IMI Value(Friend)* was significantly positively correlated with Goal SOQ ( $r = 0.468, p = .019^{**}$ ). *IMI Value(Self)* was significantly positively correlated with Goal SOQ ( $r = 0.758, p < .001^{***}$ ). *IMI Value(Stranger)* was significantly positively correlated with Goal SOQ ( $r = 0.550, p = .006^{**}$ ).

*FSQ Balance(Friend)* was not significantly positively correlated with Comp SOQ ( $r = 0.387, p = .092$ ). *FSQ Balance(Self)* was significantly positively correlated with Comp SOQ ( $r = 0.614, p = .004^{**}$ ). *FSQ Balance(Stranger)* was not significantly correlated with Comp SOQ ( $r = 0.350, p = .131$ ). *FSQ Balance(Friend)* was not significantly correlated with Win SOQ ( $r = 0.101, p = .671$ ). *FSQ Balance(Self)* was significantly positively correlated with Win SOQ ( $r = 0.544, p = .013^*$ ). *FSQ Balance(Stranger)* was not significantly positively correlated with Win SOQ ( $r = 0.094, p = .693$ ). *FSQ Balance(Friend)* was not significantly correlated with Goal SOQ ( $r = 0.150, p = .528$ ). *FSQ Balance(Self)* was not significantly correlated with Goal SOQ ( $r = 0.397, p = .083$ ). *FSQ Balance(Stranger)* was not significantly positively correlated with Goal SOQ ( $r = 0.132, p = .578$ ).

*FSQ Absorption(Friend)* was not significantly positively correlated with Comp SOQ ( $r = 0.432, p = .057$ ). *FSQ Absorption(Self)* was not significantly positively correlated with Comp SOQ ( $r = 0.317, p = .173$ ). *FSQ Absorption(Stranger)* was not significantly correlated with Comp SOQ ( $r = 0.432, p = .057$ ). *FSQ Absorption(Friend)* was not significantly correlated with Win SOQ ( $r = 0.399, p = .081$ ). *FSQ Absorption(Self)* was not significantly positively correlated with Win SOQ ( $r = 0.082, p = .733$ ). *FSQ Absorption(Stranger)* was not significantly posi-

tively correlated with Win SOQ ( $r = 0.274, p = .243$ ). *FSQ Absorption(Friend)* was significantly positively correlated with Goal SOQ ( $r = 0.563, p = .010^{**}$ ). *FSQ Absorption(Self)* was significantly positively correlated with Goal SOQ ( $r = 0.448, p = .048^{*}$ ). *FSQ Absorption(Stranger)* was not significantly positively correlated with Goal SOQ ( $r = 0.546, p = .013^{*}$ ).

### 7.2.4 Qualitative Analysis

Out of the 20 players, 13 players stated that they prefer to compete with their friends, 6 players stated that they prefer to compete with themselves, and 1 player stated that he prefers to compete with a stranger. When they were asked whether they are most likely to perform better when they are competing with a stranger, friend or themselves: 12 players answered friendly competition, 1 player answered competing with a stranger, 6 players answered self competition, and 1 player answered both friendly competition and self competition. These results show that majority of the players preferred friendly competition and felt that they would perform the best when competing with a friend. Their comments to open ended questions asking reasons for their preference of friendly competition included phrases such as "*challenge is more personal*", "*more satisfaction in a win*" and "*wanted to beat the friend the most by far*". One particularly intriguing comment was "*enjoyed the aspect of racing against a friend in privacy while still being competitive*" which showed that the player liked to compete with a friend's model in privacy as opposed to directly competing with the friend. Players who preferred self competition typically commented along the lines of "*challenging myself is the best way to track improvement*". The player who preferred competing with a stranger commented that because he had a personal relationship with the friend he would rather compete with a random stranger who he did not care about so much.

### 7.2.5 Discussion

My hypothesis was that social interactive feedforward using enhanced friends' models could improve performance and intrinsic motivation more than enhanced self-models. The results show that using an enhanced friend's model significantly improves performance when compared to an enhanced self-model with a medium

effect size and significantly improves performance when compared to an enhanced stranger's model with a large effect size. The fact that the enhanced stranger's model and the friend's enhanced model move at the same pace with the only difference being the player's association of the enhanced model shows that feedforward effect is elicited in the Friend condition leading to significant improvement in performance.

The results also show that players also exhibited significantly higher enjoyment levels when doing the Friend condition than doing the Self condition with a small effect size and Stranger condition with a large effect size. This result also shows that the player's association of the enhanced model with their friend improves enjoyment. This finding is in-line with other studies showing that inclusion of a social element of interacting with friends during a game increases enjoyment. Since the enjoyment subscale is the main self-report measure of intrinsic motivation which in turn is an important predictor of exercise adherence, social interactive feedforward shows potential in increasing exercise adherence. The results also show that players put in higher effort when doing the Friend condition than when doing the Self condition with a small effect size and the Stranger condition with a large effect size.

This implies that players are likely to exert the most effort in the social interactive feedforward context. The results show that the effect of competitor on perceived pressure was not significant. This contradicts my earlier finding which showed that players perceived higher pressure in the non-self competition condition. This could imply that difference in players' competitiveness could vary perceived pressure. The results show that the balance of challenges and skills was not significantly affected by the competitor. The results also show that players felt a significantly higher balance of challenges and skills when doing the Friend condition than when doing the Stranger condition with a small effect size. However, balance of challenges and skills was not significantly higher in the Friend condition when compared to the Self condition. The players show significantly higher absorption in the task in the Friend condition than in the Self condition with a medium effect size and in the Stranger condition with a large effect size. This indicates that players are more likely to enter a state of flow in the Friend condition than in the Self condition and the Stranger condition.

**Correlation of performance with sports orientation:**

The results of the correlations of competition orientation with performance during the Friend, Self, and Stranger conditions are likely to imply that the more competitive a player is the better they performed in the conditions Friend, Self and Stranger. The effect size of the correlation of Competition orientation and performance in the Self condition is smaller than that in the Stranger and Friend conditions. This shows that relatively more people who were not competitive by nature were also likely to perform well in the Self Condition than in the Stranger and Friend conditions. The results of the correlations of win orientation with performance during the Friend, Self, and Stranger conditions are likely to imply that the more win oriented a player is the better they performed in the conditions Friend, Self and Stranger. The effect size of the correlation of Win orientation and performance in the friend condition is larger than that in the Stranger and Self conditions. This shows that the more win oriented a person is, the more likely they are to perform well in the Friend Condition than in the Self and Stranger conditions. The results of the correlations of goal orientation with performance during the Friend, Self, and Stranger conditions are likely to imply that the more goal oriented a player is the better they performed in the conditions Friend, Self and Stranger. The effect size of the correlation of Goal orientation and performance in the Self condition is smaller than that in the Stranger and Friend conditions. This is likely to imply that relatively more people who were not goal oriented by nature were likely to perform well in the Self Condition than in the Friend and the Stranger conditions.

**Correlation of enjoyment with sports orientation:**

The results of the correlations of competition orientation with enjoyment during the Friend, Self, and Stranger conditions are likely to imply that the more competitive a player is, the more they enjoy the Friend, Self, and Stranger conditions. The effect size of correlation of Competition orientation and enjoyment in the friend condition is smaller than that in the Stranger and Self conditions which shows that relatively more people who weren't competitive were more likely to enjoy the Friend condition than the Self and the Stranger conditions. The results show that the enjoyment during the Friend, Self and Stranger Conditions were

not significantly correlated with Win orientation. This is likely to imply that enjoyment in the Friend, Self and Stranger conditions does not depend on whether they are win oriented. The results show that the enjoyment during the Friend condition was not significantly correlated with Goal orientation. This is likely to imply that players didn't have to be goal oriented to enjoy the Friend condition. The enjoyment during the Self and the Stranger Conditions were significantly positively correlated with Goal orientation with a large effect size. This is likely to imply that the more goal oriented a player is, the more they enjoyed the Self and the Stranger condition.

#### **Correlation of effort with sports orientation:**

The effort exerted during the Friend, Self and Stranger conditions was not significantly correlated with Competition orientation. This is likely to imply that the effort exerted by player does not depend on whether they are competitive. The results of correlation of effort with win orientation are likely to imply that, the effort exerted by player does not depend on whether they are win oriented in the Friend and the Self conditions but the more win oriented they are, the more effort they exert in the Stranger condition. The effort exerted during the Friend, Self and Stranger conditions was not significantly positively correlated with Goal orientation. This is likely to imply that the effort exerted by player does not depend on whether they are goal oriented in the Friend, Self and Stranger conditions.

#### **Correlation of pressure with sports orientation:**

The results of correlation of pressure experienced by players during the Friend, Self, and Stranger conditions on competition orientation are likely to imply that the pressure experienced by players during the Friend, Self and Stranger conditions might not depend on how competitive they are. The results of correlation of pressure experienced by players during the Friend, Self, and Stranger conditions on win orientation are likely to imply that the more win oriented players are, the more likely they are to feel pressure during the Stranger condition but this does not apply for Friend and Self conditions. The pressure experienced by players during the Friend, Self and Stranger conditions was not significantly positively correlated

with goal orientation. This is likely to imply that the pressure experienced by the player does not depend on whether they are goal oriented in the Friend, Self and Stranger conditions.

### **Correlation of value with sports orientation:**

The results of correlation of value experienced by players during the Friend, Self, and Stranger conditions on competition orientation are likely to imply that the more competitive a player is the more they valued the Friend and Self conditions. The effect size of the correlation of Competition orientation and value in the Friend condition is smaller than that in the Self conditions. This shows that relatively more people who were not competitive by nature were also likely to value the Friend Condition than the Self condition. The results of correlation of value experienced by players during the Friend, Self, and Stranger conditions on win orientation are likely to imply that the more win oriented a player is the more they valued the Friend and the Self conditions. The effect size of the correlation of Win orientation and value in the Friend condition is smaller than that in the Self condition. This shows that relatively more people who were not win oriented were also likely to value the Friend Condition than the Self. The results of correlations of value experienced by players during the Friend, Self, and Stranger conditions with goal orientation are likely to imply that the more goal oriented a player is, the better they performed in the conditions Friend, Self, and Stranger. The effect size of the correlation of Goal orientation and value of the Friend condition is smaller than that in the Stranger and Friend conditions. This is likely to imply that relatively more people who were not goal oriented by nature were likely to perform well in the Friend Condition than in the Self and the Stranger conditions.

### **Correlation of Balance of Challenges and Skills with Sports orientation:**

The results of correlations of balance of challenge and skills experienced by players during the Friend, Self, and Stranger conditions with competition orientation are likely to imply that the more competitive a player is the more they perceived a balance between challenges and skills in the Self condition and competitiveness does not play a role in the perceived balance of challenges and skills during the Friend and Stranger conditions. The results of correlations of balance of challenge

and skills experienced by players during the Friend, Self, and Stranger conditions with win orientation are likely to imply that the more win oriented a player is the more they perceived a balance between challenges and skills in the Self condition and win orientation does not play a role in the perceived balance of challenges and skills during the Friend and Stranger conditions. The results of correlations of balance of challenge and skills experienced by players during the Friend, Self, and Stranger conditions with goal orientation are likely to imply that goal orientation of a player does not impact the balance of challenges and skills in the Friend, Self, and Stranger conditions.

### **Correlation of Absorption in the task with sports orientation:**

The results of correlations of absorption in the Friend, Self, and Stranger conditions with competition orientation are likely to imply that competitiveness of a player does not impact the absorption of the task in the Friend, Self and Stranger conditions. The results show that the absorption in the Friend, Self and Stranger conditions were not significantly positively correlated with win orientation. This is likely to imply that win orientation of a player does not impact the absorption of the task in the Friend, Self and Stranger conditions. The results of correlations of absorption in the Friend, Self, and Stranger conditions with goal orientation are likely to imply that the more goal oriented a player is, the more absorbed they are in the Friend, Self and Stranger conditions. The effect size of correlation of Goal orientation and absorption in the Self condition is smaller than that in the Stranger and Friend conditions. This is likely to show that relatively more players who are not goal oriented also feel absorbed in the Self condition than in the Friend and Stranger conditions.

### **Impact and Implications for Exergame Design using Social Interactive Feedforward**

My results indicate that social interactive feedforward is indeed effective in improving performance and intrinsic motivation compared to self interactive feedforward. Results indicate that even when the enhanced models move at the same pace, the mere association of the enhanced model with their friend results in a rapid improvement in performance and motivation which implies that

social feedforward was successfully elicited by using an enhanced friend's model. This widens the application of conventional feedforward to a wide range of social options which enables players to also reap the benefits of socialising in addition to feedforward benefits. This method can be easily retrofitted into existing games to gain similar benefits. My study discusses the implication of correlations of sports orientations which are win/competition/goal are likely to react differently to the nature of the competitor which suggests that sports orientation should also be taken into account for personalising gamification techniques in exergaming. An intriguing problem with social interactive feedforward is that it is only suitable for players who have similar fitness levels as their friends to avoid underwhelming or overwhelming exergaming experiences. This limitation can be addressed by adapting the exergame intensity according to the player experience reflected by their affective state.

## 7.3 Conclusion

I proposed and evaluated social interactive feedforward, a novel method that combines social interaction with conventional interactive feedforward. Social interactive feedforward is based on training and competing with an enhanced model of a friend. My empirical study suggests the following conclusions, which should be considered in light of the aforementioned limitations:

1. Social interactive feedforward can be effective in further improving players' performance and intrinsic motivation when compared to conventional feedforward.
2. The main limitation of social interactive feedforward is that it is not suitable for players who are significantly less or more fit than their friends to avoid underwhelming or overwhelming exergaming scenarios respectively.
3. Social interactive feedforward can possibly cater to a wider range of players by enabling affective adaptation of its game and exercise intensity.

Social interactive feedforward has potential to be an effective intervention to improve exercise adherence. The upcoming chapters explore how to recognise the affective state of the player in an exergame in order to enable affectively adaptive



feedforward.

## Part III

# Affectively Adaptive Interactive Feedforward

## Chapter 8

# Optimal Player Experience

*“Optimal experience is that rare occasion when we feel a sense of exhilaration, a deep sense of enjoyment that is long cherished and that becomes a landmark in memory for what life should be like.”*

---

*Mihaly Csikszentmihalyi*

Optimal player experience could be the key to exercise adherence because positive and rewarding consequences when doing an activity leads to recurring behaviour [10]. This chapter discusses the various degrees of player involvement. I provide the review of various levels of immersion and elaborate the characteristics of flow.

### 8.1 Optimising Player Experience for Better Exercise Adherence

The video gaming industry is one of the fastest growing powerful global industries and has been widely successful in providing a positive player experience. User Experience (UX) is defined as a person’s perceptions and responses that result from the use or anticipated use of a product, system or service by the international

standard on ergonomics of human system interaction, ISO 9241-210 [95]. User experience is assessed by using a wide range of degrees of involvement such as engagement, presence, immersion, flow and it encapsulates the user's affect, preferences and behaviour during use [95, 182].

Evaluating the affective state, motivation, perception, and attention along with relevant determinants of the UX, such as its quality, intensity will facilitate the profiling of experiences [182]. There are instances when people feel highly involved in an activity without necessarily enjoying the experience or resulting in a change of affective state. However, I don't want to profile that kind of a player experience because the aim of my game is enjoyment which is an important factor intrinsic motivation which in turn leads to exercise adherence. Therefore, the goal of this study is to record and identify player experience that leads to feeling positive or negative affect.

Behaviourist theories and social learning theory state that re-occurrence of a behaviour is likely when it is accompanied by a positive consequence whereas punishing consequence results in its termination [10, 279, 307]. Therefore, maximising enjoyability of exercise and minimising unpleasant effects such as fatigue and discomfort could further promote adherence [10]. According to optimal experience theories [79, 81] flow – an optimal and enjoyable experience – can occur when a person's skills match the challenge of a task.

When the task is more challenging than a person's skills it leads to anxiety, whereas if a person is more skilled than the challenge level of the task it leads to boredom. Therefore, it is important to adapt the challenge level to enable optimal player experience. High intensity VR exergames that can determine player experience and dynamically adapt its exercise and game intensities to optimise immersion [55] and enjoyment [6, 124, 291] is a promising method to improve exercise adherence.

## 8.2 Immersion

Immersion is defined as a psychological state in which one perceives being enclosed by an environment providing a continuous stream of stimuli and experiences [356]. Witmer et al. list determinants that impact immersion as separation

from the outside world, perception of self inclusion in the virtual environment, instinctive interaction mechanisms, and perception of self-movement. They state that immersion depends on perceiving oneself as a part of the dynamic stream of sensory inputs and actions that both influence the viewer's activities and that are influenced by those activities.

Brown and Cairns identify three distinct levels of immersion which are engagement, engrossment and total immersion [55]. Engagement is the response of a user to an interaction that captures, preserves and stimulates their attention especially when they are intrinsically motivated [180]. This is described to be the lowest level of involvement and to lower the barriers to enter this level, the gamer needs to invest time, effort, and attention which increases for more immersive experiences [55]. The experience of being engaged in an activity lacks the emotional attachment which is observed in the deeper levels of immersion. In the second level of immersion, engrossment, game features combine to the extent that gamer's emotions are directly affected by the game and the controls become invisible [182]. Total immersion is defined as shutting off from the real-world so much so that the game is all that matters [182].

Jennett et al. identified five experiential sub-components of immersion which are cognitive involvement, real-world dissociation, challenge, emotional involvement, and control [182]. Their paper investigates the quantitative definition of immersion. They found that players in the immersive condition show a different change in eye movements over the passage of time than the players in the non-immersive condition. Their results show that eye movements increase in the non-immersive condition due to higher distraction and eye movements in the immersive condition significantly decreased over time.

A positive correlation was found between immersion and appeal. This implies that high immersion in a game may lead to high appeal, or vice versa [69]. Christou et al. found a correlation between immersion and appeal for all combinations of player experience and game played, and for all players who took part in the experiment. This implies that appeal and immersion are closely associated [69].

## 8.3 Flow

Flow is an optimal intrinsically enjoyable, subjectively effortless psychological state and can lead to peak performance in sports [110, 179, 251]. When a person is in a state of flow, they experience a number of positive characteristics such as freedom from self consciousness, greater enjoyment of the process while ignoring fatigue and discomfort [237]. When a state of flow is induced harder challenge results in lesser subjective effort and self regulatory fatigue leading to lesser perceived exertion [88, 237]. All these characteristics of flow would make the experience of playing an exergame more enjoyable and thus inducing flow is highly desirable.

The state of flow is characterized by nine components which are focused concentration on the present activity, sense of control over one's actions, merging of action and awareness, autotelic experience, loss of self-consciousness, loss of time awareness or time acceleration, clear proximal goals, unambiguous feedback, and dynamic balance between challenge and skill [178, 179]. These components are regarded as correlated dimensions determining the intensity of flow [239]. The most intense, complex, and ordered flow state is experienced if the level of all components is highest whereas if not all the levels of these components are highest it results in an overall less intense state of flow [239].

Seah et al. state that immersion is considered to be a precursor of flow [298]. Flow overlaps with immersion and both experiences have many mutual properties: concentration, distorting time perception, a balance between the player's skills and the game's challenge, and loss of self-awareness [182]. Michailidis et al. conclude that the terms of flow and immersion can be used interchangeably, until further behavioural and neurophysiological evidence is provided [233]. Regardless of whether immersion is as extreme as flow or not, immersion is an engaging positive user experience that could potentially distract the user from the physical exertion caused by exercising thus making the exergame more enjoyable [110, 179, 251].

## 8.4 Summary

This chapter provides an overview of various types of player experiences. Optimal player experience is desirable because it could potentially be the key to exercise

adherence [10], it is important to track player experience which will enable us to dynamically adapt the game. The next chapter discusses monitoring player experience by recognising and tracking the affective state of the player when they are playing an exergame.

## Chapter 9

# Affect Recognition and Tracking

*“It’s not enough that we build products that function, that are understandable and usable, we also need to build products that bring joy and excitement, pleasure and fun, and yes, beauty to people’s lives.”*

---

*Don Norman*

In order to track the affective state, one has to understand the different kinds of affective states that are relevant to monitoring the user experience. The scope of this study is to identify positive, negative, and neutral user experiences. Therefore, this chapter discusses the different kinds of user experiences that could be reflected by positive and negative affective state of the user. Affective state can be tracked by many different ways such as recognising facial expressions or using psychophysiological sensors. I compare the pros and cons of the different affect tracking methods in the context of exergaming and also review previous studies on affective gaming and exergaming. In the following chapters, player experience tracking and affect tracking are sometimes used interchangeably. This is because of my assumption that the player experience is reflected by the current affective state of the player while using an application.



## 9.1 Positive Affect, Negative Affect, and Inducing an Affective State

Positive affect, i.e. enjoyment, plays an important role in motivating people to continue playing a game [323]. Immersion in games is pivotal to enjoyment [182] and media technology development pursues immersion as a route to enjoyment [157]. A study by Liu et al. confirmed that immersion is a strong and direct determinant of user enjoyment and self-reported performance in computer game playing [211].

Immersion, presence, flow, psychological absorption and dissociation are a progression of ever-deeper indicators of game involvement [54]. All these experiences play a critical role in game enjoyment, which in turn increases intrinsic motivation and promotes adherence. All of them could lead to positive affect and improve player experience.

Experience fluctuation model partitions the user experience in to eight states which are represented as sectors of a challenge by skill Cartesian space in (Fig. 9-1) [222,223]. The state of flow is achieved when there is balance between challenges and skills, and both challenges and skills are greater than their weekly average. The model provides a detailed characterization of negative affective states such as anxiety, worry, apathy and boredom, all defined as imbalances between challenges and skills.

Anxiety is defined as a feeling of apprehension or nervousness. According to this model, it occurs when the challenge level is greater and skill level is lower than the weekly average. Worry is defined as an unpleasant feeling of panic which occurs when challenge level is the weekly average but the skill level is lower than the average. Apathy is defined as an absence of positive emotions or excitement which occurs when the challenge level and the skill level are lower than the weekly average. Boredom is defined as lack of interest which occurs when skill level is the weekly average and the challenge level is lower than average. Apathy, boredom, worry and anxiety are all negative user experiences that lead to unpleasant feelings or negative affect.

Sweetser et al. integrated heuristics into a validated model that can be used

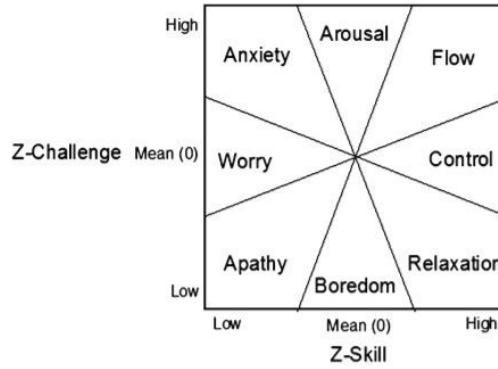


Figure 9-1: The experience fluctuation model of the flow state [110]

to design, evaluate, and understand enjoyment in games [317]. My experiment is designed to follow the criteria listed in order to induce flow. Sinclair et al. put forth the dual flow model which consists of two dimensions: attractiveness and effectiveness of the exercise [306]. In their model, the attractiveness of an exergame is a psychological model balancing the player's perceived skill with perceived challenge.

Effectiveness is the physiological counterpart of flow and is the physical balance between fitness and intensity which is the challenge of the exercise on the body. Exergames must pose an adequate load particularly intensity, duration and density for optimal adaptation [154]. Furthermore, they must be attractive and adaptive to provide a low barrier to entry for newcomers while providing enough challenge for more experienced users in order to keep the users interested [154]. I designed my exergame based on these models to induce positive affect and negative affect.

## 9.2 Affect Tracking and Affective Gaming

The cross-cultural studies of Ekman et al. show that facial expressions are reliable indicators of affective state [109, 194]. Affective state can be tracked by recognising facial expressions [74]. However, there is a variation of 25% [75] or more in emotion expression which likely occurs due to culturally specific prescriptions of emotion display rules, temperament, personality, and socialization [74].

This could potentially mean that psychophysiological measurements which in-

indicate the biological underpinnings of emotional processing controlled by the autonomic nervous system are more reliable indicators of affective state as they are reflexive and involuntary [202, 240]. Several studies have been successful in identifying and monitoring the affective state reflecting the user experience by using neuropsychophysiological sensors such as heart rate variability, skin conductivity, EEG, and fMRI, which indicate increased autonomic nervous system activity [248, 249, 256, 257].

The term “affective ludology” coined by Nacke et al., refers to the branch of study that deals with scientific measurement of emotional and cognitive aspects of player experience while interacting with games [247]. An approach to affective game design based on several high-level design heuristics states that the affective game should dynamically adapt the challenge, game content and offer assistance according to the player’s emotional state [137]. In order to do so, the first step is to identify the player’s emotional state. There is evidence showing player’s state of arousal corresponds with the pressure used to press buttons on a gamepad [318]. However, it is a correlation with stress rather than enjoyment as not all players enjoy stressful games.

Several studies describe the use of facial electromyography (EMG) as a measure of positive and negative emotional valence during video gaming [159, 248]. A study by Hazlett uses facial electromyography to calculate positive and negative affective valence during a video game. A video review identified positive and negative events during the game. The zygomaticus muscle EMG was significantly higher during positive events than negative events and the corrugator muscle EMG was significantly higher during negative events [159].

A study by Nacke et al. explored various characteristics of gameplay experience using questionnaires and psychophysiological measures [248]. They altered the Half-Life 2 game and tested three different levels in the game. One level was designed to induce boredom by using a same level layout, unchallenging opponents and gameplay, recurring characters, dreary sounds, no winning situation and no surprises. Another level was designed to be immersive by using a rewarding gameplay, exploratory environment with many features to discover, incrementally challenging level and engaging aesthetics. The third level was designed to evoke

flow by using focusing on the events,tempo and difficulty level than on the game environment. They tracked electromyography (EMG), electrodermal activity (EDA) and gathered questionnaire responses. Their results showed that it is possible detect an affective pattern from the various level designs which shows potential in detecting affecting responses of gameplay at run-time. This study was extended to test the effectiveness of electroencephalography. The results showed that the immersion level evokes greater activation in the theta band which implies an association between virtual spacial navigation and theta activity. Their studies show that gameplay experience can possibly be identified with psychophysiological measures such as electroencephalography (EEG), electromyography (EMG), and electrodermal activity (EDA).

Balducci et al. built two different game levels aimed to evoke boredom and flow and tracked the electroencephalography measurement [18]. Boredom is elicited by using linearity and recurrence with unchallenging, weak plot-story and unappealing aesthetics. Flow is achieved in the game level by designing an intrinsically rewarding level that is optimally challenging and players feel that controls are autonomous and intuitive. They did an empirical investigation with a brain-computer interface headset. They extracted numerical data features and used machine learning techniques to classify various tasks in the gaming sessions to test if the variation in levels coincide with the emotional responses.

Several studies use a hybrid or a multimodal approach of an array of sensors like heart rate monitor, EMG and galvanic skin response (GSR) to recognise affect in videogaming [255–257]. Nogueira et al. present a method to recognise valence and arousal based on skin conductivity, heart rate, heart rate variability and facial electromyography [257]. The first classification layer uses regression models to normalise all the sensor inputs and correlate each sensor input with arousal or valence. The second classification layer uses decision trees to merge the regression inputs into valence or arousal identification.

### 9.3 Affective Exergaming

Measures such as galvanic skin response, heart rate variability, EEG, facial EMG can be used to detect different kinds of user experiences like flow [248],

immersion [249], arousal [255–257]. Some physiological measures of arousal are open to corruption in games that require fast muscle reflexes to play [138] and thus, may not be suitable for exergames. Furthermore, many of these measures are likely to get affected by exercising which involves perspiration, panting and movement.

Previous studies have been successful in detecting affect in moderate intensity non-VR exergames by using one or more of the following indicators of affective state: facial expressions, GSR, temperature, respiration [243–245]. Muller et al. used exercise game design elements evoke emotional responses in a moderate intensity non-VR exergame [245]. They show that exergame elements are able to elicit emotions. Muller et al. presented their work on affectively adaptive moderate intensity non-VR exergame [244]. The story changes according to the player’s affective responses. They recognise affect based on facial expressions and electrodermal activity (EDA) measurements with significantly more robust emotion recognition rates. In their follow-up study, they used electrodermal activity, respiration, temperature sensor, and facial expressions to track affective responses. They found that psychophysiological measurements improves their previous analysis method [243]. However, their studies cannot be applied in the context of high intensity VR exergaming. Facial expression recognition in high intensity VR exergaming is difficult because players wear a VR headset which covers half their face. High intensity exercise protocols are also a lot more physically demanding as they require 80 to 90% of their peak oxygen uptake when compared to moderate intensity exercise protocols which require 50 to 60% of their peak oxygen uptake [283]. Therefore, high intensity exercise also leads to higher to higher perspiration, temperature and respiration changes which could affect the physiological measurements of the sensors recognising affective state. The Laban movement analysis (a human movement interpretation method that provides movement analysis) to recognise emotions was also tested using a moderate intensity non-VR exergame and not in high intensity VR exergames [363]. In order to recognise affect in VR exergames, I need to identify psychophysiological measures that are suitably robust.

## 9.4 Valence and Arousal

Valence and arousal of affect both need to be measured to conclude the emotional state. Previous studies have used sensors that show both arousal and valence such as the following neuro psychophysiological sensors: fMRI [8], facial electromyography [59], EEG [65], and electrocardiogram [250]. However, most of these sensors are too sensitive to be used in an exergaming environment and there are many practical difficulties when using them due to motion artefacts.

Therefore, I am not considering EMG, EEG, and ECG in my studies. For example, fMRI cannot be used in a laboratory setting [65, 237]. Facial EMG works by measuring muscle activity of facial muscles associated with smiling and frowning. It cannot be used in the context of VR exergaming as it is easily affected by movement and the exaggerated breaths taken by a player as a result of panting in addition to perspiration. ECG works by detecting the electrical signals produced by heart beat which could be affected by the raised heart rate during exercising. EEG is also extremely sensitive to movement and perspiration.

GSR measures the changes in electrical conductance of skin as a result of increased sympathetic nervous system activity. It increases with increased emotional arousal and not emotional valence. A recent study has attempted to determine both valence and arousal from only GSR data by using feature extraction of the GSR data [14]. However, this was not done with high intensity VR exergaming and therefore, their method of feature extraction to measure valence most likely is not applicable in my experiment because of extensive movement and perspiration.

However, even though a sensitive feature extraction program like theirs might not work in measuring affect in high intensity VR exergaming, skin conductance might still be useful. The skin conductance response is measured from the eccrine glands. These glands are located all over the body and are particularly dense in the palms and soles of the feet. It is important to note that these glands are different from the apocrine sweat glands. On the positive side, the eccrine glands on palms and soles are more sensitive to affect than exertion-induced perspiration [50, 80, 122] and affective responses typically precede the appearance of sweat. Therefore, GSR could potentially be suitable for measuring emotional arousal in VR exergames.

Pupil dilation, blink rate, and eye movements are potential measures of affect. Increases in pupil size reflect arousal associated with increased sympathetic activity [52, 164] and have been proposed for use in affective computing [267]. Pupil dilation is regulated by locus coeruleus-norepinephrine system in the brain which controls physiological arousal and attention [104]. Increases in the size of the pupil of the eye have been found to accompany the viewing of emotionally toned or interesting visual stimuli [164]. The pupil response during affective picture viewing reflects emotional arousal associated with increased sympathetic activity [52]. Another study shows that pupil size was significantly larger while viewing emotionally arousing sounds and discusses the possibility of using pupil size variation as a input signal in affective computing [267].

A study by Sescousse et al. shows evidence in favour of a negative relationship between spontaneous eye blink rate and dopamine activity [299]. Dopamine is a hormone and a neurotransmitter which plays a major role in motivational salience [19, 217, 346]: a type of attention which drives one's behaviour towards or away from an event [274, 346]. The reward stimulus i.e. positive reinforcers also causes strong dopaminergic activation [53]. This implies that blink rate is negatively correlated to dopamine activity which could reveal emotional valence. The magnitude of change of frequency of eye blink rate depends on interest value of video stimuli i.e. interesting video stimuli tend to suppress blink rates and boring stimuli tend to increase them [167]. During high concentration tasks, blink duration was found to be lower and inter-blink interval (IBI) was significantly higher [360].

Similarly, another study shows that when exposed to a relevant stimulus, blink rate gradually diminishes before onset and peaks just after offset [127]. The prevalent inference of various studies on blink rate suggest that attention leads to a reduction in blink frequency, with the magnitude of blink inhibition being proportional to attentional demands [312]. Based on related studies, I investigate if blink rate reduces when a person is experiencing increased emotional arousal and positive valence in VR exergaming.

Several studies show that direction of gaze fixations are in line with one's thoughts and are directed towards the object of one's thoughts [114, 148, 325]. This implies

that analysing gaze fixations could shed light on more nuanced emotional experiences of players suggesting that they could also be markers of affective experiences. Based on these considerations, I decided to investigate the potential of skin conductance, pupil dilation, blink rate and gaze fixations for affect recognition in VR exergaming.

## 9.5 Experience Sampling

Experience sampling is a well established method for measuring experiences immediately as they are perceived in a particular moment [161]. The immediate sampling of experience decreases the chance of failing to remember and the inclination to select answers based on social desirability [367]. A person's knowledge of recently received information is saved in their short term memory which is ephemeral in nature with a limited storage capacity [286]. It only moves to long term memory upon rehearsal or meaningful association which implies that there is risk of some experience getting lost in the translation [129]. As a result, experience sampling is preferable to post-experience questionnaires for measuring instantaneous affective response, therefore, I used it to collect ground truth data about affect. To prevent the process of experience sampling from interrupting delicate player experiences such as immersion and flow, I integrated experience sampling directly into a VR exergame.

## 9.6 Summary

Immersion, presence, flow, psychological absorption, and dissociation are all indicators of game involvement of varying degrees. They could lead to game enjoyment i.e. experiencing positive affect. Conversely, apathy, boredom, worry, and anxiety are indicators of negative player experiences and they could lead to feeling negative affect. Positive and negative player experiences could be tracked by using neuro-psychophysiological sensors such as facial EMG, heart rate monitor, EEG [248, 249, 256, 257].

However, some of these sensors are incompatible for use in the context of high intensity VR exergaming because they are very sensitive in nature and they



are likely to get affected by the perspiration, panting, and excessive movement. Based on careful review of studies using psychophysiological sensors, I conclude that skin conductance, pupil dilation, blink rate, and gaze fixations can possibly be appropriate for tracking the affective state in high intensity VR exergaming. The next chapter presents an empirical study to recognise positive and negative affective state in high intensity VR exergaming.

# Chapter 10

## Affect Recognition in High Intensity VR Exergaming

*“Your intellect may be confused,  
but your emotions will never lie  
to you.”*

---

*Roger Ebert*

### 10.1 Introduction

Affective state is a highly significant predictive value of usability in exergaming [42]. According to the FitForAll exergaming study by Billis et al., positive affective state experienced as a result of the exergame amplified the usability. Therefore, they conclude, dynamic adaptation of game content according to the player’s affective state would most likely result in better adherence and motivation [42]. Previous studies have been successful in recognising affect in moderate intensity non-VR exergames using a combination of psychophysiological measurements and facial expressions [243–245] and body motion features [363]. However, affective recognition in *high intensity VR exergaming* has not yet been achieved. It presents unique challenges as the increased physical exertion and the VR headset interfere with those affect recognition methods. Studies generally rely on tedious self-reported user experience measures or questionnaires at the end of

the experiment, which are useful to get overall feedback but lack the capacity to measure genuine and unadulterated reactions to events and experiences in the game [159]. Furthermore, they are redundant feedback in a sense, as they cannot be used to dynamically adapt the VR exergame during the session. Video taping of the game play and asking the player to reflect on their experience relies on recollection from remote memory which may not be reliable. Similarly, deciphering body language and facial expressions of players either at run-time or based on video tapes of the game sessions might not be effective because the transitory nature and subjective variation of expressing emotions via facial expressions and body language. Furthermore, these complications are compounded in the context of high intensity VR exergaming. It is difficult to recognise facial expression while wearing a VR Head-Mounted Display (HMD), and facial expressions are affected by excessive panting and flared nostrils as a result of high intensity exercise. The player experience is extremely fragile and can be disrupted by verbal enquiries of user experience as cognitive effort is necessary to express emotional experience in words [159].

Affectively adaptive videogames have been extensively studied; they use various neuropsychophysiological correlates such as blood pressure, heart rate variability (HRV), electroencephalography (EEG), facial electromyography (EMG), and galvanic skin response (GSR) to recognise affect [18,249,255–257]. Applying these measures in the context of an exergame imposes many challenges, as variations in some psychophysiological parameters may not be an autonomic response but due to physical activity. For example, perspiration can affect skin conductivity, and raised heart rate can affect heart rate variability. EMG signals can be distorted from exaggerated breaths because the oral cavity tends to become wider during exhaustion to facilitate higher intake of oxygen. Another problem of affect recognition is that common measures such as heart rate and skin conductance primarily reflect arousal and do only a limited job at best of indicating emotional valence, i.e. at distinguishing whether the affect is positive or negative [159].

The aim of this study is to identify psychophysiological markers of positive and negative affect that are suitable for use in the context of VR exergaming. I conducted two experiments to achieve my aim. This thesis' fourth experiment compares the impact of physical exertion and gamification on psychophysiological

measurements during rest, conventional exercise, VR exergaming, and sedentary VR gaming. I used an eye tracker and skin conductivity sensor to test the suitability of different psychophysiological measures in determining affective responses. I also used validated questionnaires to determine user experience at the end of each condition and correlated them with the measures. In the thesis' fifth experiment, I recorded players' affective responses during 'underwhelming', 'overwhelming' and 'optimal' VR exergaming scenarios. I used experience sampling to elicit a ground truth of the affective state, and then correlated the psychophysiological measures with the ground truth as well as validated questionnaires of user experience. The measures that correlate significantly are thereby identified as predictors of affective state in high intensity VR exergaming.

In summary, I investigated the following research questions:

- RQ1** How do affective responses differ between sedentary gaming, exergaming, conventional exercise, and rest?
- RQ2** Which psychophysiological sensors are most suited for determining affect in high intensity VR exergaming?
- RQ3** What are the psychophysiological correlates of positive and negative affect in high intensity VR exergaming?

I have made the following contributions to this field of research

1. A qualitative and quantitative analysis of differences between player's affective responses to VR gaming, VR exergaming, conventional exercise, and rest.
2. A novel method to measure positive and negative affect in VR exergaming.
3. An empirical study investigating the psychophysiological correlates of positive and negative affect.

To the best of my knowledge, my study is the first of its kind to investigate the use of pupillometry and skin conductivity to recognise affective state in high intensity VR exergaming.

Exercise (within participants)	Game (within participant)	Phase				
		P-I (60s)	P-II (30s)	P-III (90s)	P-IV (30s)	P-V (90s)
No Exercise (N)	No Game (N)	Rest	Rest	Rest	Rest	Rest
No Exercise (N)	Game (G)	Game	Game	Game	Game	Game
Exercise (E)	No Game (N)	Warm Up	Sprint 1	Recovery	Sprint 2	Cool down
Exercise (E)	Game (G)	Warm Up	Sprint 1	Recovery	Sprint 2	Cool down

Table 10.1: Experimental design overview.

## 10.2 Experiment IV: Gaming and Exercise

### 10.2.1 Experimental Design

In order to address RQ1 and identify suitable psychophysiological sensors (RQ2), I investigated the difference in affective responses to sedentary VR gaming, high intensity VR exergaming, and conventional high intensity exercise. The overall experimental design is summarised in Table 10.1. I used a within-participants design for the independent variables *Game* with levels game (G) and no game (N), and *Exercise* with levels exercise (E) and no exercise (N). Outcome variables were measured during each of five *Phases* P-I, P-II, P-III, P-IV, and P-V, which were defined based on a high intensity interval training (HIIT) exercise protocol. The combination of no-exercise and no-game forms the baseline condition (B) in which players remain seated in all five phases. In the sedentary gaming condition (G), players play a VR game that is an exact replica of my VR exergame, but the forward motion in the game is simply controlled by a hand pedal attached to the handlebar of the bike. The G condition includes avoiding the trucks by moving laterally. In the conventional exercise condition (E), players exercise without the game in all five phases according to the HIIT protocol. And in the VR exergaming condition (EG), players play my VR exergame, which gamifies the HIIT protocol.

The method of acceleration (exercycle vs. hand pedal) was a potential confounding factor in the VR game experience, therefore, I devised a model for the hand pedal that yielded a similar experience of acceleration as the exergame. Similar to the exergame where acceleration is becoming increasingly difficult, the acceleration effects of the pedal were attenuated with increasing speed. Similar to the exergaming condition, players of the sedentary game were asked to maintain a virtual speed of “65 to 70 RPM” during the low intensity phases and go as fast as they can



Figure 10-1: Exergame setup for experiments IV and V consisting of the exercise bike, the FOVE headset with eye tracking capabilities, skin conductivity sensor, and the hand pedal. The hand pedal is attached to the handlebar of the bike.

during the high intensity sprints. To avoid further confounding factors, players wore an HMD in all conditions.

The conditions B and E were identical in terms of the VR environment and the only difference was the mode of control. The main purpose of the conditions B and E was to record psychophysiological measurements during rest and conventional exercise conditions respectively. Adding interesting graphics or gameplay to conditions B and E would introduce confounding factors as players would be distracted. It was also important to maintain the same lighting across B,E, G, and EG conditions. Therefore, the VR environment of conditions B and E was bare but used the average sky colour and the average ground colour of the G and EG conditions. Prompts and information about timing and speed were shown not only in EG but also in E and G. I recorded the baseline B first to get resting skin conductivity and blink rate before any other activity. After recording the baseline B, the order of G, E, and EG was counterbalanced.

During the G condition, players held the hand pedal in their left hand and the skin conductivity sensor was attached to their right hand to minimise movement artefacts. In order to differentiate sweat from affective response from exercise sweat, I measured skin conductivity at the fingers, which primarily contain eccrine glands highly responsive to emotional stimuli. I consistently used the same exercise protocol in conditions E and EG and ensured players rested between conditions to control for the effects of exercise on sweating. Adding more interesting graphics to the G condition and not to the EG condition will affect the pupillometry results due to difference in the graphics introducing confounding factors. Therefore, the conditions G and EG were completely identical in terms of both gameplay and graphics and the only difference was the mode of control.

The experiment set-up is shown in (Fig. 10-1). Screenshot of the low intensity phase of the baseline condition is shown in (Fig. 10-2) (top) and the high intensity phase of the baseline condition is shown in (Fig. 10-2) (bottom). The Exercise condition looks identical to the baseline condition except for the additional exercise prompts and cycling speed displayed in addition to the timing in the baseline condition. Screenshot of the low intensity phase of the exergame condition is shown in (Fig. 10-3) (top) and the high intensity phase of the exergame condition

is shown in (Fig. 10-3) (bottom). The Game condition looks identical to the exergame condition.

**Realistic simulation of EG condition in G condition:** In the EG condition, players were advised to cycle at a RPM of 65 to 70 during the low intensity sessions and sprint as fast as they could during the high intensity sessions. They could easily reach a speed of 60 with minimal effort and it progressively became more difficult to reach higher RPMs. Even the physically fit players did not normally exceed an RPM of 180. Since the G condition is controlled by a hand pedal it is possible for the players to reach any speed by continuously pressing the hand pedal which might lead to confounding factors as they will be much faster in the G condition than in the EG and E conditions. To avoid this, I simulated a progressively difficult acceleration of speed in the game only (G) condition. When the pedal is pressed and the speed is less than 60, the speed will be accelerated by a unit of 1. Similarly if the speed is between 60 to 100, the speed will be accelerated by a unit of 0.1. If the speed is between 100 to 150, the speed will be accelerated by a unit of 0.05. If the speed is over 150, the RPM will be accelerated by a unit of 0.005. This results in a similar speed emulation as the EG condition with the only difference being the usage of the hand pedal instead of cycling. Furthermore, similar to the EG condition, players were asked to maintain a speed of 65 to 70 during the low intensity phases of the Game only condition (G) and were told to go as fast as they could during the high intensity phases.

### 10.2.2 Exergame Design

Our VR Exergame (Fig. 10-1) is a cycling based game played by riding a stationary exercise bike while wearing a head mounted device. I used a modified version of the exergame I used in the previous experiments. In this section, I have described the VR exergaming condition of this experiment.

**Exercise Protocol:** I use an exercise protocol called high-intensity interval training (HIIT) for both the experiments. This involves short intermittent bouts of vigorous high intensity exercise, interspersed with low-intensity exercise [131]. It is a time efficient alternative to conventional low or moderate intensity exercise protocols while being just as effective as them [130]. The HIIT protocol I used



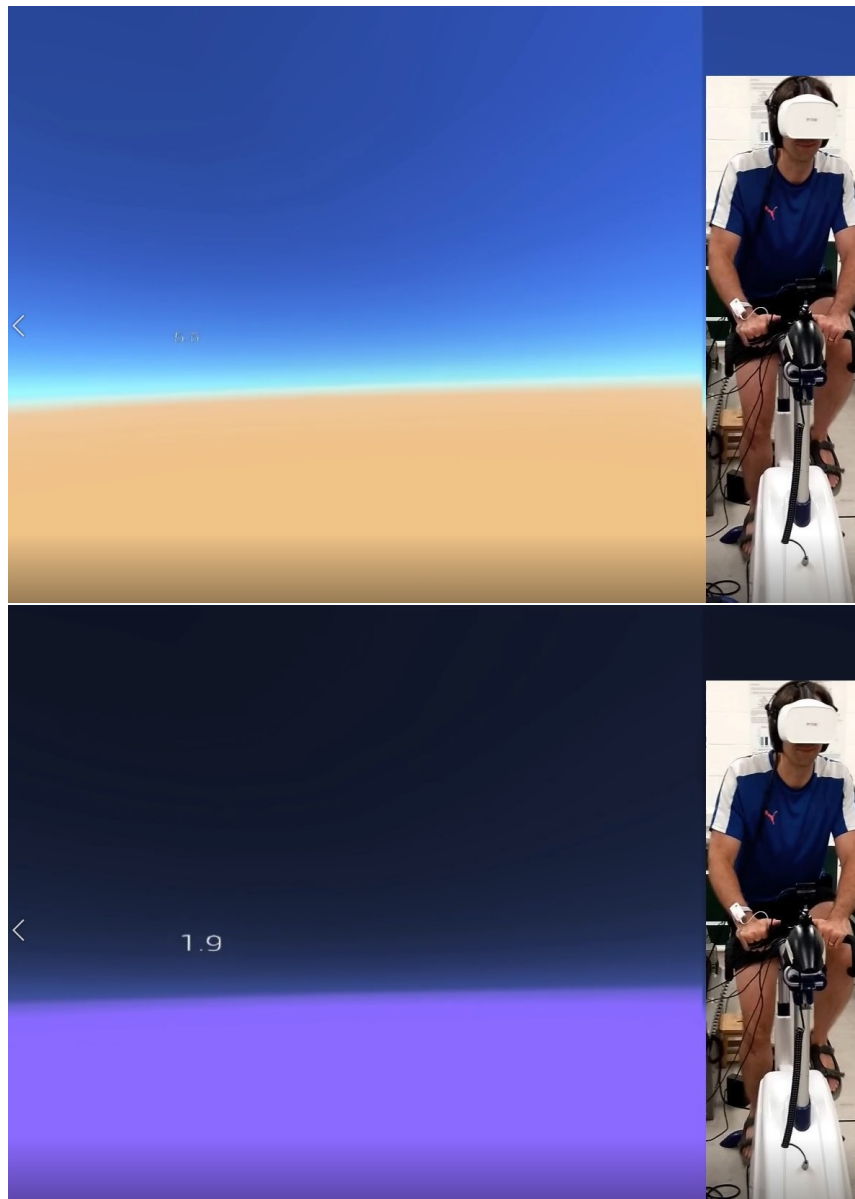


Figure 10-2: Screenshots of the low-intensity phase (top) and the high-intensity phase (bottom) in the baseline session. The exercise session looks similar to the baseline session except for additional exercise prompts and cycling speed displayed in the center in addition to the timing.



Figure 10-3: Screenshots of the low-intensity phase (top) and the high-intensity phase (bottom) in the exergame session. The game session looks similar to the exergame session except for additional exercise prompts and cycling speed displayed in the center in addition to the timing.

consists of a 60 sec warm-up phase. This is followed by two 30 sec sprint sessions (S1 and S2) which are separated by 90 sec recovery phase in between them. The protocol finishes with a 90 sec cool-down phase. During the warm-up (W), recovery (R), and cool-down (C) phases, players cycle at a low intensity of 65 to 70 RPM and a low cadence of 12 Nm. During the sprint sessions, players cycle as fast as possible at a higher cadence to prevent uncontrolled movements. Initially, the resistance is set to 0.4 Nm kg<sup>1</sup> based on the player's body mass and it is adjusted to suit the player during the familiarisation phase.

**Aesthetics:** In this experiment, the aim of my aesthetic design is to relax my players during the low intensity phases i.e. warm-up, recovery, and cool-down and to motivate and energise my players during the high intensity sprint phases as explained in 5.2.1. I play music with a tempo of 120 beats per minute. During the high intensity phases, the environment transitions into a dark scene with police cars flashing emergency lights to instigate the player to cycle faster. Players were told that they had to out-run the police to try to get a stronger sense of urgency. I play the same music with a more powerful tempo of 140 beats per minute.

**Mechanics:** The player cycles along a straight path. The game speed is proportional to the pedalling speed of the exercise bike calculated by revolutions per minute shown by the cycle's sensors (RPM). The lateral movement of the player is enabled by leaning to the left or to the right. The speed of lateral movement is proportional to the roll angle measured by the HMD sensors. The RPM and time remaining in the current phase are displayed in the screen. Directions for the intensity of the phase is displayed before the phase starts at the centre of the HMD.

**Game Play:** In the VR exergame condition of my this experiment, trucks appear during the low intensity phase. The player is instructed to avoid trucks by moving laterally. Players start the game with a score of 100 points. If the player collides with a truck, 10 points are deducted. In the high intensity section, a competitor appears and the player's goal is to beat the competitor. In the first 30 sec sprint, the game is programmed to allow the player to be ahead of the competitor for the first 10 seconds and in the next 20 seconds, the competitor will be sped up to be ahead of the player. In the second 30 sec sprint, the competitor will be sped

up to be ahead of the player for the first 10 seconds and in the next 20 seconds the competitor will be slowed down to allow the player to get ahead. This is to ensure a close match and an engaging race between player and the competitor. Points are awarded after the successful completion of their exercise protocol in proportion to the distance covered by them. Visual components of the game such as the distance between the player and the competitor, the points, prompts, RPM, and the timer are constantly displayed on the screen.

**Adherence to flow models:** I designed the VR exergame according to the dual flow model and the game flow model which describe the designs to elicit flow [306,317]. The psychological challenge of the VR exergame is to avoid trucks and the physiological challenge of the VR exergame is to cycle. The VR exergame is scalable to the ability of the individual in order to impose a level of challenge that is close to optimal which is more engaging, immersive and increases the chances of entering the state of flow [83,182].

**Equipment:** I used a Lode Excalibur Sport exercise bike and a FOVE HMD. They were connected to a PC running Unity with an Intel Xeon E5 2680 processor, 64 gigabytes of RAM, and two NVIDIA Titan X graphics cards running in SLI mode.

### Outcome Variables

I collected psychophysiological measurements that are known to be associated with affect, considering their averages over the five phases for each condition. I measured blink rate in blinks per minute (*Blinks*) with the eye gaze tracker built into the FOVE HMD, recording pupillometry data with FOVE's Unity plugin at approx. 160Hz and counting blinks as periods with zero pupil diameter. I measured the tonic skin conductance (*Conductivity*) in microsiemens (S) at 128 Hz using the Shimmer3 Consensus GSR development kit. Furthermore, I recorded the average power output (*Power*) in Watts during the sprint phases in conditions E and EG as a measure of physical performance, using the serial port interface provided by the Lode Excalibur Sport exercise bike.

I collected ground truth data for affect based on the Intrinsic Motivation Inventory (IMI) [288], which was validated in numerous sports science studies [70,225]. I

used the main Interest/Enjoyment subscale (*IMI Enjoy*) with a scoring range from 1 to 7, with 7 being the highest intrinsic motivation score. Players answered the questionnaires on a PC next to the bike. They got off the bike and were provided with a chair.

### 10.2.3 Procedure

I recruited 18 players (14 male, 4 female, age 19-32, mean  $23 \pm 3$ ), who were students and employees of the University of Bath. I screened them with the Physical Activity Readiness Questionnaire (PAR-Q) [326] and excluded players with health risks or a resting blood pressure greater than 140/90 mmHg. The remaining players were informed about all experimental conditions and asked to complete a demographics questionnaire. After initialising sprint resistance based on body mass, players went through a familiarisation phase which allowed them to experience the VR exergame. Players then performed each of the four conditions: B, G, E, and EG. They were instructed to work “very hard” during the sprints and to maintain 65-70 RPM during the low intensity phases for both EG and E. After conditions G, E, and EG, players completed the IMI and left qualitative feedback about their experience. Players had a break of approx. 10 minutes between the gameplay rounds to avoid fatigue. They were allowed to take longer breaks if they were tired. At the end of the experiment players were asked to comment on their experience during the different conditions. Each session took approx. 120 minutes.

### Hypotheses

Research suggests *Blinks* is lower and *Conductivity* is higher for higher levels of enjoyment [80, 312]; so I hypothesise:

- H1** EG is more enjoyable than E and G as measured by *IMI Enjoy*.
- H2** *Conductivity* correlates positively with enjoyment as measured by *IMI Enjoy* in conditions E and EG.
- H3** *Blinks* correlates negatively with enjoyment as measured by *IMI Enjoy* in conditions E and EG.

Demographics	Variable	B	G	E	EG
n=18	Power	-	-	289.52 $\pm$ 80.92	329.74 $\pm$ 61.16
m=14; f=4	IMI Enjoy	-	3.60 $\pm$ 1.42	3.60 $\pm$ 0.99	5.67 $\pm$ 0.84
age=23 $\pm$ 3	Blinks	123.06 $\pm$ 113.28	41.94 $\pm$ 58.26	110.39 $\pm$ 112.78	64.83 $\pm$ 74.55
	Conductivity	1.73 $\pm$ 0.99	3.93 $\pm$ 3.39	5.24 $\pm$ 3.16	5.95 $\pm$ 3.47

Table 10.2: Demographics and results for Experiment IV (avg. $\pm$ std. dev.).

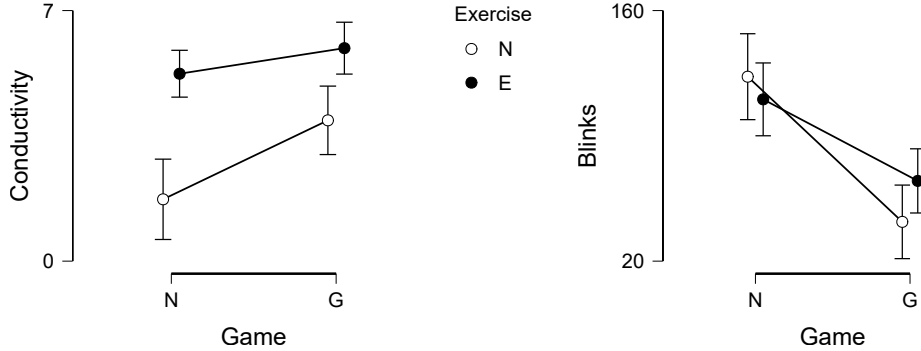


Figure 10-4: Conductivity (left) and Blinks (right) in the four conditions of Experiment IV.

## 10.2.4 Results

The results are summarised in Tables 10.2 and 10.3. The assumptions of analysis of variance (ANOVA) were met, so I analysed the data with repeated-measures ANOVAs using the  $\omega^2$  measure for effect sizes [263], and two-tailed t-tests with Holm correction for pairwise comparisons. According to power analyses, the ANOVAs were able to detect medium-sized effects (Cohen's  $f=0.286$ ) and the t-tests were able to detect large effects (Cohen's  $d=0.701$ ) at  $\alpha = 0.05$  with a power of 0.8. They allow us to better understand the uncertainty in the test results. Because of my within-participants design, I calculated and tested repeated measures correlations using the `rmcorr` R package [44] instead of simple Pearson correlations. This accounts for the individual differences between players in both psychophysiological and self reported measurements, and increases the statistical power as no aggregation of measurements is necessary when testing intra-individual hypotheses [17]. The level of significance used for all tests was  $\alpha = .05$ . Plots show 95% confidence intervals of the means.

**Manipulation Check:** A one-way repeated-measures ANOVA was conducted on E, G and EG for *IMI Enjoy*. The main effect was significant ( $F(2, 34) = 26.11, p < .001^{***}$ ) with a large effect size ( $\omega^2 = 0.427$ ). The differences between E and EG ( $t(17) = 6.778, p < .001^{***}$ ), and G and EG ( $t(17) = 6.328, p < .001^{***}$ ) were significant. The difference between G and E was not significant. The results show that players enjoyed the exergame more than conventional exercise and sedentary gaming, as intended, so I accept H1.

**Psychophysiological Differences:** A two-way repeated-measures ANOVA was conducted on *Game* (N vs. G) and *Exercise* (N vs. E) for *Conductivity* (Fig. 10-4 left). The effect of *Game* was significant ( $F(1, 17) = 11.994, p = .003^{**}$ ) with a medium effect size ( $\omega^2 = 0.065$ ). The effect of *Exercise* was also significant ( $F(1, 17) = 33.132, p < .001^{***}$ ) with a large effect size ( $\omega^2 = 0.203$ ). The interaction effect of exercise and game was significant ( $F(1, 17) = 4.694, p = .045^*$ ) with a small effect size ( $\omega^2 = 0.016$ ). The difference in *Conductivity* between E and EG was significant ( $t(17) = 2.370, p = .015^*$ ).

A two-way repeated-measures ANOVA was conducted on *Game* (N vs. G) and *Exercise* (N vs. E) for *Blinks* (Figure 10-4 right). The effect of *Game* was significant ( $F(1, 17) = 26.168, p < .001^{***}$ ) with a medium effect size ( $\omega^2 = 0.108$ ). The effect of *Exercise* was not significant indicating that exercise did not affect *Blinks* much. The interaction effect of exercise and game was significant with ( $F(1, 17) = 6.247, p = .023^*$ ) and a small effect size ( $\omega^2 = 0.009$ ). The difference in *Blinks* between E and EG was significant ( $t(17) = 3.607, p = .001^{**}$ ).

**Psychophysiological Correlates:** A repeated-measures correlation analysis for the conditions E and EG showed that *Conductivity* was significantly positively correlated with *IMI Enjoy* ( $r(17) = 0.418, p = .038^*$ ), so I accept H2. *Blinks* was significantly negatively correlated with *IMI Enjoy* ( $r(17) = -0.574, p = .005^{**}$ ), so I accept H3.

**Qualitative Feedback:** Comments indicate that players enjoyed being in an aesthetically appealing VR environment and experiencing the gamification of high intensity exercise. Typical comments in the VR exergaming condition were “challenging, thrilling, immersive”, “combines best of both worlds, makes exercising way more enjoyable”. Some comments such as “could push myself harder” suggest

that, in addition to being entertained by the VR exergaming experience, players also felt more motivated to exercise.

### 10.2.5 Discussion

The manipulation check showed that the VR exergame was successful in eliciting positive affect (H2). The significant effects of *Game* and *Exercise* on *IMI Enjoy* indicate that they can both enhance positive affect (RQ1), and this is supported by the qualitative feedback. As a consequence, I can compare the conditions to find psychophysiological markers of positive affect. As I am interested to find markers specifically, for VR exergames, the measurements in E and EG are most relevant, as players were exercising at high intensity and using an HMD in both of these conditions.

The significant effect of exercise on *Conductivity* indicates that the sensor measurements are indeed affected by the exercise, increasing skin conductivity due to sweat. However, the effects of gamification on *Conductivity* while exercising were still significant, indicating that it is still sensitive enough as a marker of affect in a high intensity VR exergame. The correlation analysis confirms, as suggested in related work, that *Conductivity* is a linear predictor of positive affect, with more positive affective states leading to a higher skin conductivity.

The effect of exercise on *Blinks* was not significant, indicating that the sensor measurements are robust against the effects of exercise. There is a significant effect of gamification on *Blinks* both for sedentary activities (B vs. G) as well as while exercising (E vs. EG), making it a promising choice for affect recognition in general and for high intensity VR exergaming in particular. The correlation analysis confirms, as suggested in related work, that *Blinks* is a linear predictor of positive affect, with more positive affective states leading to a lower blink rate. Since *Blinks* appears to be a good choice for measuring affect in high intensity VR exergames, I widen my range of pupillometry measurements to also include gaze fixations and pupil dilation in Experiment V.



Variable	IMI Enjoy
Conductivity	H2 *0.418
Blinks	H3 **-0.574

Table 10.3: Correlation coefficients of Experiment IV.

## 10.3 Experiment V: Correlates of Affect

### 10.3.1 Affect Elicitation in High Intensity VR Exergaming

In order to identify the psychophysiological correlates of positive and negative affect in high intensity VR exergaming, I will have to first evoke those affective states in players. I provide an overview of advances in affect elicitation methods to identify the most effective method to be used in my experiment.

#### Affect elicitation and user experience simulation

Affective state is defined as a mental experience caused by neurophysiological variation linked to feelings with positive or negative valence. I consider affect as a two-dimensional model based on Russell's affect grid model, which describes affect along the dimensions of valence and arousal. User experience is defined as perceptions and responses resulting from the use of a system [95], so it is reflected in the current affective state of the user.

Effective affect elicitation is an integral part of psychological studies. Studies use a variety of ways to induce different affective states. One of the most widely used methods in affective studies is the use of standardised collection of pictures called IPAC (International Affective Picture System) [73, 92, 280]. Another extensively used method in emotion research to induce emotion is film clips, which are dynamic in nature and combine visual and auditory stimuli [143, 338]. Similar to affect elicitation in psychological studies, many gaming studies have attempted to induce different user experiences. Moller et al. invoked overwhelming, underwhelming and optimal player experiences by tweaking the game intensity [237]. Nacke et al. induced different player experiences, flow, immersion and boredom via game level design modifications [248]. These studies show that media are powerful affective stimuli.

Game aesthetics is defined as the sensory phenomena encompassing visual, aural,

haptic and other elements that the player encounters in the game [252]. It is very powerful as it is capable of evoking desirable emotional responses in the player [172]. Visual and aural stimuli such as bells, sirens, flashing lights and dramatic hues can increase aesthetic satisfaction in a game by providing feedback to the player and acting as a reward for continued participation [165,357]. Several studies show the ergogenic effect of music in sports and high intensity exercise performance by shifting attentional focus away from agonising exercise induced bodily sensations [34,43,56,191]. Motivational tracks include a high tempo beat over 120 beats per minute and a strong rhythm to enhance energy and induce bodily action [190]. Based on these studies I evoked underwhelming, overwhelming and optimal states in high intensity VR exergames by varying the aesthetics and gameplay.

### 10.3.2 Experimental Design

In order to determine the suitability of different psychophysiological sensors (RQ2) and analyse the correlates of positive and negative affect in a high intensity VR exergame (RQ3), I designed three VR exergame scenarios to evoke the following three states: an *optimal* state (Opt) to induce positive affect, an *underwhelming* state (Under) to induce neutral affect, and an *overwhelming* state (Over) to induce negative affect.

This is similar to Moller et al., who elicited a state of flow in players by tweaking the game intensity using overwhelming, underwhelming and optimal conditions [237]. However, my focus is not on flow as flow is often regarded as an extreme positive experience [182]. The aim of my experiment is to find the correlates of a broader spectrum of positive *and* negative affective states, therefore, I used intrinsic motivation (*IMI Enjoy*) as a measure of affect instead of flow. The three states Opt, Under and Over form the levels of the independent variable *Game Scenario*, and I investigated the effects of Game Scenario on psychophysiological correlates using a counterbalanced within-participants design. I used a methodology extended from Experiment IV, with the notable addition of experience sampling to record ground truth values of affective responses.

In addition to *Conductivity*, *Blinks* and *Power*, I measured pupil dilation and gaze

fixations. The relationships of *Conductivity*, *Blinks* and pupil dilation with affect have been well documented [52,80,164,312]. Gaze fixation is only a partial indicator of a person’s thoughts as gaze may convey the object of a person’s thoughts, which may not necessarily indicate affective state. Similarly, even though many studies explored the relationship between task performance and enjoyability [169,208], better performance does not necessarily mean higher enjoyment. In summary, *Conductivity*, *Blinks*, and pupil dilation are more “conventional” predictors of affect, although they have not been explored yet for high intensity VR exergames, while gaze fixations and *Power* are more speculative in their relationship to affect.

### 10.3.3 Exergame Design

I modified the VR exergame from Experiment IV to create VR exergaming environments for the optimal, underwhelming, and overwhelming scenarios. To avoid confounding factors, the game mechanics, HIIT exercise protocol, equipment, ambient lighting, and overall game environment in all three scenarios stayed the same. Because all conditions used the same exercise protocol, the noise due to movement artefacts when measuring *Conductivity* was similar and comparable. The aesthetics and gameplay specifications of the different exergaming conditions are summarised in the table Tables 10.4.

**Aesthetics:** In my fifth experiment, I have simulated the underwhelming, optimal and overwhelming conditions by creating three different VR exergaming environments. To avoid confounding factors, I have used the same exercise protocol, lighting and game environment in all the three VR exergaming environments. The underwhelming condition is designed to evoke boredom by using minimal aesthetics. There are no sound effects or music throughout and during the sprint session the police cars don’t appear. The optimal condition is designed to be engaging by presenting the player with the same appealing aesthetics described above in the VR exergaming condition of my fourth experiment. The overwhelming condition is designed to stress the player by using annoying, noisy sound effects like blaring horns during the low intensity phases and wailing police sirens during the high intensity phases instead of music. The underwhelming scenario was designed to be devoid of stimuli and evoke boredom by using minimal aesthetics, without sound effects or music and no police cars with flashing lights. There was

a complete absence of gameplay elements such as scoring points, dodging trucks and racing a competitor. The overwhelming condition was designed to elicit stress and frustration by using ‘annoying’, noisy sound effects such as blaring horns during the low intensity phases and wailing police sirens during the high intensity phases instead of music.

**Game Play:** In this experiment, I used a colour coded experience sampling scale to measure affect valence and arousal as very negative (-2), negative (-1), neutral (0), positive (+1) and very positive (+2). The scale is integrated into the game and players are able to indicate their user experience instantaneously without stopping the game to make it as unobtrusive as possible. The scale appears 30 seconds after the warm up session starts and 5 seconds after the 1st sprint gets over and 5 seconds after the 2nd sprint gets over, in all the three conditions: underwhelming, optimal and overwhelming. The scale appears on the screen for 10 seconds each time and accepts input from two hand pedals attached to the handlebar of the exercise bike. If players felt positive affect, they were instructed to click their right hand pedal once or twice depending on their arousal. Similarly, if they felt negative affect, they were instructed to click their left hand pedal once or twice. If their affective state was neutral, they were instructed to click both the pedals once.

In the underwhelming condition of my fifth experiment, in addition to no music or sound effects, there is no game play. The player cycles in the same environment with a complete absence of gameplay elements such as scoring points, dodging trucks and racing a competitor. Trucks don’t appear in the low intensity phases and police cars and a competitor doesn’t appear in the high intensity phases. The aim of this phase is to underwhelm the player thus leading her to experience negative affect. Figure 10-5 shows screenshots of the low-intensity and the high-intensity phases in the underwhelming condition.

The optimal condition is designed to present the player with an optimally challenging game play. It is similar to the VR exergaming condition of the fourth experiment in terms of game play and aesthetics. The only difference is that in both the 30 sec sprints, the competitor will be sped up to be ahead of the player for the first 10 seconds and in the next 20 seconds the competitor will be

Gaming Scenario	Exercise Protocol	Aesthetics	Game Play
Underwhelming	W, R, C	No sound effects	No trucks to dodge No points
	S1, S2	No sound effects	No police cars No competitor
Overwhelming	W, R, C	Loud honking	Trucks to dodge 20 points deducted on collision
	S1, S2	Blaring sirens	Chased by police cars Unbeatable competitor
Optimal	W, R, C	120 bpm music	Trucks to dodge 10 points deducted on collision
	S1, S2	140 bpm music	Chased by police cars Beatable competitor

Table 10.4: Experiment Design Overview of Experiment V

slowed down to allow the player to get ahead. This is to ensure that the player "wins" and finds the game enjoyable thus experiencing positive affect. Figure 10-6 shows screenshots of the low-intensity and the high-intensity phases in the optimal condition.

The overwhelming condition is designed to be stressful to the player. The game play is extremely challenging. The competitor appearing during the sprint conditions is programed to be always ahead of the player and the player loses 20 points if they hit a truck. The aim of this phase is to overwhelm the player thus leading her to experience negative affect. Figure 10-7 shows screenshots of the low-intensity and the high-intensity phases in the optimal condition.

### Outcome Variables and Data Analysis Approach

In addition to recording *Conductivity*, *Blinks* and *Power* to determine affective state, I recorded the total time of eye gaze fixations (*Fixations*) on visual components of the game: the competitor, the gap between the player and the competitor, the points, prompts, the displayed RPM and the timer i.e. I chose all the dynamic visual components in the game. The rest of the components made up the outer environment. I used ray casting to detect the game components corresponding



Figure 10-5: Screenshots of the low-intensity phase(top) and the high-intensity phase(bottom) in the underwhelming condition.



Figure 10-6: Screenshots of the low-intensity phase(top) and the high-intensity phase(bottom) in the optimal condition.



Figure 10-7: Screenshots of the low-intensity phase(top) and the high-intensity phase(bottom) in the overwhelming condition.



to a point of gaze. A low *Fixations* value indicates that the player was looking more at the peripheral VR environment or ‘staring at nothing’ instead of paying attention to the game. I also recorded a player’s pupil dilation (*Pupil*) during the warm up and in each of the two sprints, considering their average. Similar to Experiment IV, I used the IMI Interest/Enjoyment subscale (*IMI Enjoy*) to measure intrinsic motivation. Lastly, the experience sampling method integrated in the exergame was used to collect ground truth values about the player’s affective state; I consider the average of all values measured in a condition (*Affect*). I matched the sensor data and the ground truth by taking the average of the sensor data and of the experience sampling measures over a whole gameplay session.

*Conductivity*, *Fixations* and *Pupil* values are affected by systematic individual differences in eccrine activity [293, 294], fixation length [162, 163] and pupillary sensitivity [170], respectively. This experiment allowed us to collect enough data from each player under VR exergaming conditions to compensate for these individual differences by normalising the variables using standard z-score transforms. *Fixations* and *Pupil* values were centred at the player mean and scaled by dividing them by a player’s standard deviation. *Conductivity* values were not centred and only divided by the standard deviation, as they are only used as a predictor of affect arousal, see below.

I consider affect as a two dimensional model consisting of valence and arousal based on Russell’s affect grid model [287], which describes affect along the dimensions of pleasure-displeasure (valence) and arousal-sleepiness (arousal). For this study I analyse valence as a ternary construct with three states: positive, negative and neutral, without a magnitude. Our experience sampling *Affect* scale with range  $[-2, +2]$  accommodates both these dimensions: 1) arousal is represented by the absolute value with range  $[0, 2]$ , and 2) valence is represented by the sign (+, - or neutral). Although this approach has the advantage of differentiating neutral as well as positive and negative affect, it cannot distinguish between different affective states of the same valence, similar to other works on affect recognition using psychophysiological correlates [60, 129].

From related work I know that some psychophysiological variables are indicators of affect as a whole, or at least valence (positive, neutral or negative), while some

variables are only indicators of arousal, with a valence in negative or positive direction. I formalise this by defining *Valence* as the sign of affect  $\text{sign}(Affect)$  with possible values -1, 0 and +1, and *Arousal* as the absolute value of affect  $|Affect|$  with non-negative values. Variables that predict the whole affective state, i.e. both valence and arousal, correlate directly with *Affect*. Variables that predict valence, i.e. whether the affect is negative, neutral or positive, are correlated with  $\text{sign}(Affect)$ . Variables that predict only arousal are correlated with  $|Affect|$ . These correlations can be tested using the repeated-measures correlation analysis from Experiment IV. Since I treat valence as a ternary construct here, linear repeated-measures regression is more appropriate as a model than logistic regression.

### 10.3.4 Procedure

I recruited 18 players (14 male, 4 female, age 20-44, mean  $26 \pm 5$ ). The procedure of Experiment V was similar to that of Experiment IV. I used the same screening procedure, exclusion criteria, questionnaires, and exergame familiarisation phase. Additionally, players practised answering the experience sampling scale by clicking the hand pedals, to make sure this would be easy during the experiment. Each experiment session took approximately 120 minutes.

### Hypotheses

I expect *Affect* to correlate with *IMI Enjoy* as the two concepts are highly related and both capable of measuring positive and negative affective response [95, 182]:

**H4** *Affect* correlates positively with enjoyment as measured by *IMI Enjoy*.

Related work and the results of Experiment IV suggest that *Blinks*, *Pupil*, *Fixations* and *Power* are likely to be indicative of affect as a whole in the following manner:

**H5** *Blinks* correlates negatively with *Affect*.

**H6** *Pupil* correlates positively with *Affect*.

**H7** *Fixations* correlates positively with *Affect*.

**H8** *Power* correlates positively with *Affect*.

If *Blinks*, *Pupil*, *Fixations* and *Power* correlate with *Affect*, they will by implication

Variable	Affect	Valence	Arousal
Conductivity	-0.059	-0.092	H9 *0.335
Blinks	H5 *-0.374	** -0.460	0.121
Pupil	H6 *0.346	0.270	-0.211
Fixations	H7 **0.409	***0.512	-0.115
Power	H8 *0.382	*0.296	0.116

Table 10.5: Correlation coefficients of Experiment V.

Demographics	Variable	Under	Over	Opt
n=18	Power	300.85 $\pm$ 116.76	309.23 $\pm$ 102.31	332.88 $\pm$ 113.95
m=14; f=4	IMI Enjoy	3.41 $\pm$ 1.22	4.45 $\pm$ 1.22	5.183 $\pm$ 1.10
age=26 $\pm$ 5	Blinks	103.67 $\pm$ 91.34	96.67 $\pm$ 81.38	86.83 $\pm$ 86.136
	Pupil	45.07 $\pm$ 4.57	42.33 $\pm$ 5.31	43.72 $\pm$ 4.66
	Conductivity	4.29 $\pm$ 3.04	4.40 $\pm$ 2.73	4.63 $\pm$ 2.97
	Fixations	3267.39 $\pm$ 1432.98	2777.44 $\pm$ 1319.14	3018.28 $\pm$ 1613.41
	Affect	0.24 $\pm$ 0.88	-0.30 $\pm$ 1.21	1.19 $\pm$ 0.65
	Valence	0.28 $\pm$ 0.90	-0.11 $\pm$ 0.96	0.89 $\pm$ 0.32
	Arousal	0.72 $\pm$ 0.54	1.04 $\pm$ 0.64	1.19 $\pm$ 0.65

Table 10.6: Demographics and results for Experiment V (avg. $\pm$ std. dev.).

also correlate in the same manner with valence to some degree; therefore, I am also testing their corresponding correlations with  $sign(Affect)$ . Related work shows that *Conductivity* is a more prominent indicator of arousal rather than valence:

**H9** *Conductivity* correlates positively with  $|Affect|$ .

### 10.3.5 Results

The results of Experiment V are shown in Tables 10.6 and 10.5. Similar to Experiment IV, the assumptions of analysis of variance (ANOVA) were met, so I analysed the data with repeated-measures ANOVAs and two-tailed t-tests with Holm correction for pairwise comparisons. According to power analyses, the ANOVAs were able to detect medium-sized effects (Cohen’s  $f=0.312$ ) and the t-tests were able to detect large effects (Cohen’s  $d=0.701$ ) at  $\alpha = 0.05$  with a power of 0.8. As for Experiment IV, repeated-measures correlation with *rmcorr* was used to test correlations at a significant level of  $\alpha = .05$ .

**Manipulation Check:** A repeated-measures ANOVA was conducted on Game Scenario (Over, Under and Opt) for *IMI Enjoy*. The effect of Game Scenario was significant ( $F(2, 34) = 13.873, p < .001^{***}$ ) with a ‘large’ effect size ( $\omega^2 = 0.261$ ). *IMI Enjoy* in Opt was significantly higher compared to Over ( $t(17) = 2.480, p = .012^*$ ) with a ‘medium’ effect size (Cohen’s  $d=0.585$ ) and also significantly higher compared to Under ( $t(17) = 5.497, p < .001^{***}$ ) with a ‘large’ effect size (Cohen’s  $d=1.296$ ). A repeated-measures ANOVA was conducted on Game Scenario (Over, Under and Opt) for *Affect*. The effect of Game Scenario was significant ( $F(2, 34) = 15.868, p < .001^{***}$ ) with a ‘large’ effect size ( $\omega^2 = 0.284$ ). *Affect* in Opt was significantly higher compared to Over ( $t(17) = 6.285, p < .001^{***}$ ) with a ‘large’ effect size (Cohen’s  $d=1.481$ ) and also significantly higher compared to Under ( $t(17) = 4.216, p < .001^{***}$ ) with a ‘large’ effect size (Cohen’s  $d=0.994$ ). All this shows that Opt, Over and Under were successful in eliciting significantly different levels of affect, which is necessary in order to analyse the correlations of *Affect* with the psychophysiological variables.

**Validity of Affect:** A repeated-measures correlation was conducted on Game Scenario for *Affect* and *IMI Enjoy*. *Affect* was significantly, positively correlated with *IMI Enjoy* ( $r(35) = 0.579, p < .001^{***}$ ), so I accept H4. This indicates that my experience sampling method (*Affect*) is a valid measure of affect in relation to *IMI Enjoy*.

**Correlates of Affect:** *Blinks* was significantly negatively correlated with *Affect* ( $r(35) = -0.374, p = .011^*$ ), so I accept H5. *Pupil* was significantly positively correlated with *Affect* ( $r(35) = 0.346, p = .018^*$ ), so I accept H6. *Fixations* was significantly, positively correlated with *Affect* ( $r(35) = 0.409, p = .006^{**}$ ), so I accept H7. And lastly, *Power* was significantly positively correlated with *Affect* ( $r(35) = 0.382; p = .010^*$ ), so I accept H8.

**Correlates of Valence:** *Blinks* was significantly negatively correlated with *sign(Affect)* ( $r(35) = -0.46; p = .002^{**}$ ). *Pupil* was not significantly positively correlated with *sign(Affect)* ( $r(35) = 0.27; p = .052$ ). *Fixations* was significantly, positively correlated with *sign(Affect)* ( $r(35) = 0.512; p = .001^{**}$ ). Lastly, *Power* was significantly positively correlated with *sign(Affect)* ( $r(35) = 0.296; p = 0.038^*$ ).

**Correlate of Intensity:** *Conductivity* was significantly positively correlated with */Affect/* ( $r(35) = 0.335; p = .021^*$ ), so I accept H9.

**Regression Analysis:** The combined linear effects of the psychophysiological variables on affect were analysed using multilevel linear regression models [72, 271] in R through the nlme package [45]. The psychophysiological variables were set up as fixed effects and player number was set up as grouping factor. I tested the regression coefficients for significance with  $\alpha = .05$ , based on my hypotheses, reporting their 95% confidence intervals *CI*. I first analysed the effects of *Fixations*, *Pupil*, *Blinks* and *Power* on *Affect*: the effects of *Fixations* ( $B = 0.414, CI = [0.076, 0.752], t(49) = 2.463, p = .009^{**}$ ) and *Pupil* ( $B = 0.322, CI = [-0.015, 0.660], t(49) = 1.920, p = .030^*$ ) were significant, and the effects of *Blinks* ( $B = 0.002, CI = [-0.002, 0.005], t(49) = 0.821, p = .208$ ) and *Power* ( $B = -0.001, CI = [-0.004, 0.002], t(49) = -0.663, p = .255$ ) were not significant.

This indicates that *Fixations* and *Pupil* are the most important linear predictors of *Affect* ( $R^2 = 0.246$ ), with *Blinks* and *Power* not improving the prediction significantly. I then analysed the effects of *Fixations*, *Blinks* and *Power* on *Valence*: the effect of *Fixations* ( $B = 0.456, CI = [0.196, 0.716], t(50) = 3.521, p < .001^{***}$ ) was significant, and the effects of *Blinks* ( $B < 0.001, CI = [-0.003, 0.003], t(50) = 0.005, p = .498$ ) and *Power* ( $B = -0.001, CI = [-0.003, 0.001], t(50) = -1.013, p = .158$ ) were not significant. This indicates that *Fixations* is the most important linear predictor of *Valence* ( $R^2 = 0.262$ ), with *Blinks* and *Power* not improving the prediction significantly.

Combining my results about all predictors of *Valence*, *Arousal* and *Affect*, I then analysed the effects of  $sign(Fixations) \times Conductivity$ , *Pupil* and *Fixations* on *Affect*: the effects of *Pupil* ( $B = 0.330, CI = [0.015, 0.646], t(50) = 2.106, p = .020^*$ ) were significant, and the effects of  $sign(Fixations) \times Conductivity$  ( $B = 0.466, CI = [-0.266, 1.199], t(50) = 1.279, p = .103$ ) and *Fixations* ( $B = -0.018, CI = [-0.730, 0.694], t(50) = -0.050, p = .480$ ) were not significant. After removing *Fixations* from the model, the effects of both  $sign(Fixations) \times Conductivity$  ( $B = 0.449, CI = [0.130, 0.769], t(51) = 2.823, p = .003^{**}$ ) and *Pupil* ( $B = 0.329, CI = [0.021, 0.637], t(51) = 2.146, p = .018^*$ ) were significant, indicating

that this is a suitable model ( $R^2 = 0.322$ ).

Figure 10-8 shows a graph of model predictions vs. *Affect* with regression lines for each player. The repeated-measures correlation and regression analyses are able to take these individual variations into account. The regression lines are scattered along the diagonal as each player has her own baseline levels for the psychophysiological variables and the *Affect* measurements. The repeated-measures correlation and regression analyses are able to take these individual variations into account. Combining my results about more conventional predictors of *Valence*, *Arousal* and *Affect*, I finally analysed the effects of  $\text{sign}(-\text{Blinks}) \times \text{Conductivity}$ , *Pupil* and *Blinks* on *Affect*: the effects of  $\text{sign}(-\text{Blinks}) \times \text{Conductivity}$  ( $B = 0.548, CI = [0.018, 1.078], t(50) = 2.075, p = .021^*$ ), *Pupil* ( $B = 0.379, CI = [0.054, 0.705], t(50) = 2.339, p = .011^*$ ) and *Blinks* ( $B = 0.005, CI = [-0.0004, 0.011], t(50) = 1.863, p = .034^*$ ) were all significant, indicating that this is also a suitable model ( $R^2 = 0.247$ ).

**Qualitative Feedback:** A recurring theme in Opt was positive engagement, e.g. “enticing”, “motivating” and “stimulating”. Players also commented positively on the level of challenge in Opt, e.g. “the competition was fair which made it really fun”. Comments on Under such as “dull”, “super boring” and “repetitive” resonate with its purpose to underwhelm the player. Comments about Over, e.g. “disturbing”, “annoying”, “irritating”, expressed that players were clearly frustrated. They described the level of challenge as “disheartening” and the competitor as “too fast” and “winning by so much!”.

### 10.3.6 Discussion

The results indicate that affect in VR exergames can be measured by integrating an experience sampling scale directly into the exergame, mitigating the need for more intrusive measurements. The proposed scale correlates with the widely-used and well-validated IMI Interest/Enjoyment scale (H4). However, unlike IMI it has a straightforward neutral point that facilitates interpretation, and it can be quickly applied during the experience, making it easier to collect time series data about affect.

The experiment demonstrates how affect can be manipulated in an exergame by

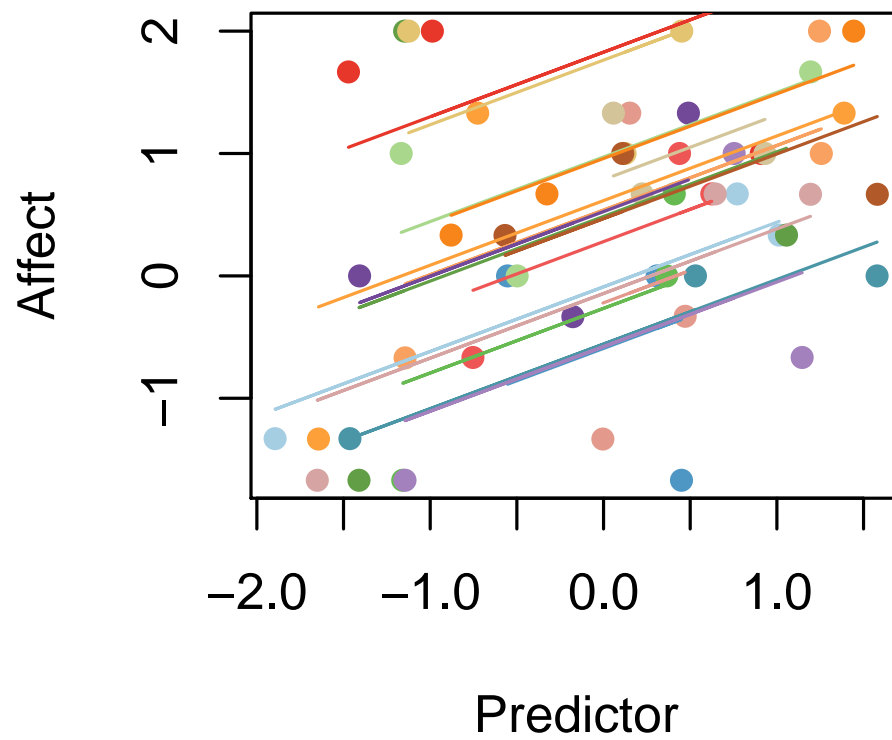


Figure 10-8: Affect is predicted from sensor measurements using regression models (here:  $\text{sign}(\text{Fixations}) \times \text{Conductivity} + \text{Pupil}$ ) with individual regression lines to represent each player.

design, based on game aesthetics and cognitive and physical challenge, making it easier for other researchers to collect new data sets on affect. This is also relevant for the calibration of affective exergames, where different affective responses need to be collected in order to determine personal parameters of affect recognition models. The main aim of my fifth experiment was to find the psychophysiological correlates of positive and negative affect (RQ3), and the hypothesised correlations (H5-H9) were all confirmed. This indicates that the identified correlates are valid for a range of affect measurements spanning positive as well as neutral and negative responses, and that they are robust enough to help predict affect in high intensity VR exergames.

While other works use machine learning approaches to recognise affect, these approaches often hide the underlying relationships between psychophysiological variables and recognised affect. By contrast, my analysis of linear relationships increases conceptual understanding and can be used as a basis to build more complex predictors modeling non-linear relationships. A main result is that measures related to the eye are promising predictors of affect in high intensity VR exergaming, and with the rise of eye-tracking enabled HMDs this is becoming increasingly relevant. In particular, the use of eye gaze fixations in this context is novel and promising, and there is potential to refine this approach by separately considering fixations on specific visual design elements of a game.

The correlation analysis confirms that not all psychophysiological measures are made equal. For example, skin conductivity is mainly a measure of arousal and blinks are more useful for predicting valence than arousal. The results also demonstrate that these measures can be combined to build stronger predictors, e.g. by estimating affect as a product of valence and arousal. The correlations shed some light on good and bad choices for sensor selection, giving system designers an idea of what can be expected from a particular psychophysiological measurement. For example, pupil dilation alone – although widely used in affective experiments – works only moderately well in a VR exergame. While predictors involving fixations can be comparatively strong, they generally need semantic information about the game, e.g. where important game elements are currently visible on the screen, which requires access to game internals. This would be difficult to obtain when recognising affect in a closed-source game, and could even be difficult if the source



code is available. By comparison, “conventional” predictors involving blink rate, pupil dilation and skin conductivity are context agnostic, i.e. they can be used independently of the experience that is measured.

Predicting psychological states such as affect is generally difficult. There is usually no straightforward predictor that is highly correlated with the desired property. Reasonable predictors combine different measures to form an overall estimate, and also reduce variance by considering individual differences between users. For example, I used individual averages and standard deviations in order to compensate for individual differences in response sensitivity and model linear affect response for specific players. While these parameters can be obtained fairly easily and mostly automatically, they do require individual calibration; so an interesting direction of future work would be how affect recognition could be calibrated continuously as part of an exergaming experience.

**Limitations:** I took repeated measures in both experiments, which means that my results may have been affected by familiarisation and fatigue. I mitigated this with a familiarisation phase, breaks and counterbalancing. Furthermore, my players were mainly in their 20s and mostly male, which may affect the generalisability of my results. Some players were not strangers to the research team, some of them participated in both experiments, and they had varying previous VR experience.

My manipulation checks indicate that this did not impact the results noticeably as all conditions were successful in eliciting the desired affective responses that could then be correlated with psychophysiological measurements. All players were naive to the goals of the experiments and all of them went through a standardised familiarisation phase in both experiments to mitigate the effects of training and previous VR experience. Focusing on an activity lowers blink rate and this is a potential limitation for Experiment 1. However, Experiment 2, which used the same game mechanics, exercise protocol, equipment, ambient lighting and overall game environment as the EG condition of Experiment 1, shows that blink rate was significantly correlated with *Affect*. My findings are in line with previous studies showing that blink rate is negatively correlated with dopamine activity [299], which is associated with affect.

Our tested correlations have ‘moderate’ to ‘large’ effect sizes, so they are likely to be useful for similar populations. However, the accuracy of the linear model could be further investigated using longitudinal studies with bigger sample sizes, e.g. to shed light on the stability of predictors over time. Exercise-related personality traits such as competitiveness may have influenced the results [136], and they could be included as covariates in future research. To increase ecological validity, future studies could be conducted in real-world conditions such as gyms to mitigate the influence of Hawthorne effects.

**Impact:** This multi sensor approach makes the predictor of affect recognition more robust. My work paves the way for affectively adaptive high intensity VR exergames that can improve adherence. My approach of determining the affective state is versatile and can be extended to apply in other contexts. It can be used in conventional high intensity exercise by using a non-VR eye tracker and skin conductivity sensor to create an adaptive work-out scheme. It can also be used in VR applications that doesn’t involve physical exercise.

## 10.4 Conclusion

I identified psychophysiological measures suitable for affect recognition in high intensity VR exergaming and determined their relationship with affect. Building on this, I proposed and evaluated a novel, robust, multisensor approach for affect recognition, which will help exergame designers to scientifically measure, personalise and optimise the player experience. The results of my experiments can inform future VR exergaming studies as they help researchers to design and test affect predictors, and to formulate hypotheses about how sensor measurements relate to affect. My data sets and analyses are available online [29].<sup>1</sup> In summary, I come to the following conclusions:

1. I identified gaze fixations, eye blinks, pupil diameter, and skin conductivity as psychophysiological measures suitable for recognising affect in high intensity VR exergaming.
2. I presented an affective predictor with an optimal combination of the psychophysiological correlates of positive and negative affect in high intensity

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<sup>1</sup><https://doi.org/10.15125/BATH-00758>

VR exergaming.

Our approach and findings can be used as a basis to design and build affectively adaptive high intensity VR exergames with great potential to improve exercise adherence.

## Chapter 11

# Conclusion: The Road Ahead to Affectively Adaptive Interactive Feedforward in High Intensity VR Exergaming

*“All our dreams can come true if  
we have the courage to pursue  
them”*

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*Walt Disney*

This chapter provides the conclusion to my PhD journey. I summarise the whole thesis giving an overview of all the chapters. The literature review in the thesis spans exergaming, social psychology, and affective computing. I present my research questions, discuss my findings, and my contributions. I formulate the guidelines for affect elicitation and tracking in high intensity VR exergaming and the challenges that I must tackle to implement affectively adaptive interactive feedforward.

## 11.1 Thesis Summary

Exercising regularly is paramount to good health. Our lifestyles have become increasingly sedentary even though from a genetic perspective, our bodies are built to be constantly physically active. This mismatch leads to dozens of chronic illnesses such as cardio-vascular diseases, cancer. The main barriers to exercise adherence are lack of time and motivation. High intensity exercise is twice as time efficient as moderate intensity exercise protocol but it could be difficult to motivate people at the required intensity. Gamification of high intensity exercising combined with immersive VR, VR exergaming, is a promising intervention to address the problem of lack of time and motivation. Feedforward is a psychophysical training technique that involves individuals observing an enhanced self-model showing previously unachieved performance levels for them to emulate resulting in rapid improvements in their performance. I presented a novel method, interactive feedforward, in which players train and compete with their enhanced self-model in an immersive, VR exergame. Consistent with the findings of previous feedforward research, the results showed that interactive feedforward significantly improves performance while maintaining intrinsic motivation.

In the second part of the thesis, I started by studying the extensive body of related work on social psychology theories. Social interaction plays a vital role in enhancing relatedness which in turn enhances self-determination leading to long term intrinsic motivation. Furthermore, social facilitation theory says that presence of others can increase one's internal drive prompting enhanced performance. Social learning theory posits that re-enacting observed modelled behaviour of others depending on whether one perceives the behaviour to be rewarding. This can be achieved by an engaging social exergame with co-players exhibiting modelled behaviour. Furthermore, social interaction with people an individual has a pre-existing positive relationship with such as a friend can improve player experience. These findings strongly affirm the importance of friend modelling. Friend-modelled feedforward relies on the neural activities underpinning the effects of self-modelled feedforward such as mirror neuron activation, mental time travel, and prospection which can also be applied for friend-modelling. I extended the interactive feedforward approach to a social context by running an empirical study and I investigated the effectiveness of friend-modelled/(Social) interactive

feedforward when compared to self-modelled feedforward. The results show that friend-modelled(Social) interactive feedforward is indeed superior to self-modelled feedforward.

However, social interactive feedforward comes with a major limitation. It can effectively be applied to co-players who are nearly of the same fitness levels to avoid underwhelming or overwhelming scenarios. This can be mitigated if the exergame is capable of detecting the player experience by recognising the affective state of the player and dynamically adapting the exergame intensity accordingly. The third part of the thesis is on affect recognition in high intensity VR exergaming. I begin by discussing the peculiar problems presented by affect tracking using psychophysiological sensors in a high intensity VR exergaming environment such as perspiration, excessive panting which could impact the sensor data. The first empirical study identified that skin conductivity and blink rate are appropriate predictors of affect in high intensity VR exergaming by analysing affective responses in the conventional exercise, rest, sedentary gaming, and VR exergaming conditions. The second empirical study analysed the affective responses in the underwhelming, optimal, and overwhelming high intensity VR exergaming scenarios. The quantitative analysis successfully identified that gaze fixations, blink rate, pupil diameter, and skin conductivity are affective predictors in high intensity VR exergaming. The next section presents guidelines for evoking different affective states and tracking it in high intensity VR exergaming.

## **11.2 Guidelines for Affect Elicitation and Tracking in High Intensity VR Exergaming**

Affective computing is a rapidly growing field in HCI. It is the study of developing affectively intelligent systems that can identify emotion and accordingly adapt their interaction for better personalisation and user experience. The foundation of affective computing is accurate and instantaneous recognition of affective state. Identifying effective affect elicitation techniques is an essential step to develop and test affect recognition methods.

The vast literature in affect recognition shows that the affective state can be

identified and tracked by various methods such as, for example, facial expression recognition and psychophysiological correlates. However, recognising the affective state in the context of VR exergaming with conventional methods can be challenging. This is because psychophysiological measurements are extremely sensitive to movement and perspiration, which cannot be avoided in VR exergaming. This chapter discusses guidelines to evoke different affective states and successfully identify their affective state in light of my findings reported in my recent research paper [28]. I also contemplate the challenges that need to be overcome to build affectively adaptive high intensity VR exergames.

Different affective states can be evoked in high intensity VR exergames by using game aesthetics and gameplay to create underwhelming, overwhelming and optimal exergaming scenarios. When tracking the affective state using psychophysiological correlates, it is important to ensure that the game mechanics, exercise protocol, equipment, ambient lighting and overall game environment in all the exergaming scenarios stay the same to avoid confounding factors.

An ‘optimal’ exergaming scenario can be created by using appealing music and optimally challenging gameplay. An ‘underwhelming’ exergaming scenario can be created by using minimal aesthetics without any sound effects and no gameplay. An ‘overwhelming’ exergaming scenario can be created by using stressful and annoying sound effects and extremely challenging gameplay.

Pupil dilation, blink rate and skin conductivity are suitable psychophysiological measures for high intensity VR exergaming. Furthermore, unconventional measures such as performance and gaze fixations are speculative indicators of affect. Ray casting can be used to detect the gameplay-related components corresponding to the point of gaze, such as a timer and speed indicator. A low rate of gaze fixations on gameplay-related components indicates that the player was focusing more on the outer VR environment or staring at nothing instead of paying attention to the game. Because all the exergaming scenarios use the same exercise protocol, the noise in the skin conductivity measurements due to movement artefacts and exercise induced sweat will be similar and comparable.

Our findings confirmed that different psychophysiological measures vary in their ability to indicate affective valence and arousal. For example, skin conductivity is

mainly a measure of arousal, and blink rate is more useful for predicting valence than arousal.

I observed that skin conductivity was affected by systematic individual differences in eccrine activity [293, 294]. Similarly, gaze fixations varied in terms of fixation length [162, 163] and pupil dilation measurements had varying individual pupillary sensitivity [170]. These individual differences can be compensated by normalising the variables using standard z-score transforms. Pupil dilation and gaze fixations measurements can be centred at the player mean and scaled by dividing them by a player's standard deviation. Similarly, skin conductivity can be divided by the standard deviation to produce a measure of arousal.

Although I have successfully identified and evaluated that skin conductivity and pupillometry measurements are suitable to use in the context of high intensity VR exergaming, I must tackle the following research and engineering problems to implement affective high intensity VR exergames:

1. Instantaneous recognition of affect is still a challenge: My studies show that there is correlation between psychophysiological measurements and self-reported player experience measurements over a period of 5 minutes. The next step is to ensure there is a correlation between instantaneous psychophysiological measurements and instantaneous self-reported user experience measurements. This step is essential to build a dynamic affectively adaptive high intensity VR exergame because each sprint session in the high intensity exercise protocol I use lasts for only 30 seconds. Therefore, in order to be effective in adapting exergame intensity according to the affective state, the system has to recognise the affective state instantaneously.
2. Psychophysiological sensors: My studies show that psychophysiological sensor data must be preprocessed by using normalisation to compensate for individual differences. This was done after the experiment data was recorded. In order to enable dynamic adaptation of the exergame according to the affective state, the elaborate process of preprocessing must be done instantaneously while the measurements are collected.
3. Stables and labiles: It has been reported that some people ("stables") are



not stimulated much by external events or internal thoughts [295], making it hard to measure affect. Similarly, some people have high skin conductivity responses in the absence of external stimuli (“labiles”). Although I did not encounter these phenomena in my study, studies with bigger sample sizes are necessary to investigate these challenges.

## 11.3 Contributions, Impact, and Future Work

Each of the three parts of my thesis presents a novel method, tests the validity using empirical studies, and presents the quantitative and qualitative analysis. The summary of my contributions are:

1. Interactive Feedforward: My thesis identifies the unique challenges of gamification of high intensity VR exergaming. It contributes the novel psychophysical training technique, interactive feedforward for high intensity VR exergaming which is successful in spurring players to achieve the required high intensity in addition to improving performance and maintaining intrinsic motivation.
2. Social Interactive Feedforward: Self-modelled interactive feedforward has been successfully extended into a social context which gives it added advantages of improved performance and motivation when compared to conventional interactive feedforward.
3. Affective Predictors in High Intensity VR Exergaming: I also present a multi-sensor approach to track the affective state in high intensity VR exergaming and provide guidelines for exergaming researchers.

The best feature of my research contributions is that, they can possibly be applied in various other applications in non-exergaming and non-VR contexts. This can be confirmed by conducting further studies. My future work will overcome the research challenges I have listed and will build on my research findings to present “Affectively adaptive interactive feedforward”.

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# Appendix A

## Forms

This chapter contains the publications contribution forms.

## Appendix 6B: Statement of Authorship

<b>This declaration concerns the article entitled:</b>			
Affect Recognition using Psychophysiological Correlates in High Intensity VR Exergaming			
<b>Publication status (tick one)</b>			
Draft manuscript <input type="checkbox"/> Submitted <input type="checkbox"/> In review <input type="checkbox"/> Accepted <input checked="" type="checkbox"/> Published <input type="checkbox"/>			
<b>Publication details (reference)</b>	Affect Recognition using Psychophysiological Correlates in High Intensity VR Exergaming		
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<b>Candidate's contribution to the paper (provide details, and also indicate as a percentage)</b>	<p>The candidate contributed to / considerably contributed to / predominantly executed the...</p> <p>Formulation of ideas: Predominantly executed idea (80%)</p> <p>Design of methodology: Predominantly the executed methodology and the experiment design (75%)</p> <p>Experimental work: Predominantly executed the user study. (100%)</p> <p>Presentation of data in journal format: I did the literature review, proposed and implemented the experiment design, programmed the exergame design for the various experiment conditions, ran the user studies, did the quantitative and qualitative analysis, and wrote the first draft of the paper. Predominantly executed the presentation of data in journal format. (80%)</p>		
<b>Statement from Candidate</b>	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature.		
<b>Signed</b>	C. Soumya Barathi	<b>Date</b>	14/4/2020

## Appendix 6B: Statement of Authorship

<b>This declaration concerns the article entitled:</b>			
Guidelines for Affect Elicitation and Tracking in High Intensity VR Exergaming			
<b>Publication status (tick one)</b>			
Draft manuscript <input type="checkbox"/> Submitted <input type="checkbox"/> In review <input type="checkbox"/> Accepted <input checked="" type="checkbox"/> Published <input type="checkbox"/>			
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<b>Statement from Candidate</b>	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature.		
<b>Signed</b>	C. Soumya Barathi	<b>Date</b>	14/4/2020

## Appendix 6B: Statement of Authorship

<b>This declaration concerns the article entitled:</b>			
Interactive Feedforward for Improving Performance and Maintaining Intrinsic Motivation in VR Exergaming			
<b>Publication status (tick one)</b>			
Draft manuscript <input type="checkbox"/> Submitted <input type="checkbox"/> In review <input type="checkbox"/> Accepted <input type="checkbox"/> Published <input checked="" type="checkbox"/>			
<b>Publication details (reference)</b>	Interactive Feedforward for Improving Performance and Maintaining Intrinsic Motivation in VR Exergaming		
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<b>Statement from Candidate</b>	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature.		
<b>Signed</b>	C. Soumya Barathi	<b>Date</b>	14/4/2020